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PSYCHROMETRIC PROPERTIES
OF
HELIUM-WATER VAPOR MIXTURES

A Study of the Relationship Between Temperature, Pressure and Humidity, and Wet- and Dry-Bulb Temperatures

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I. ABSTRACT

When gas that is not saturated with water is passed over a wetted surface, the surface temperature will drop because of evaporation of water. This drop in temperature (often called the wet-bulb depression) together with the temperature of the gas stream gives a measure of the humidity of the gas. For many years, psychrometers based on this phenomnon have been used very successfully for measuring the humidity of air under the usual conditions of temperature and pressure encountered by most people on earth.

In recent years, with man's increasing interest in exploring the ocean at greater and greater depths, it was found necessary to replace the nitrogen of the normal atmosphere with helium to provide a breathing gas for those living at ambient ocean pressure. This led to a need for a knowledge of the psychrometric properties of helium at pressures up to several hundred pounds per square inch.

This investigation has resulted in: (1) the development of an improved psychrometer, (2) the development of a psychrometric equation for the helium-water vapor system, and (3) the development of a computer program which makes it possible to print out psychrometric charts for any ocean depth.

II. INTRODUCTION

It must have been many thousands of years since man first observed that a wetted surface became cool when air blew over it. However, it was not until the middle of the eighteenth century that there is any record of this phenomenon being used to quantitatively measure the humidity of air.

During the past two hundred years, psychrometers consisting of two thermometers, one dry and the other with a bulb covered by a wetted wick, have been used extensively to measure the humidity of air (1-17). In fact, the wet- and dry-bulb psychrometer is still the most widely used instrument for humidity measurement.

As a result of numerous measurements by many individuals, we have reliable tables and charts that give the relationship between wet- and dry-bulb temperatures and relative humidity (2, 11, 17). However, these tables and charts, in most cases, are for a pressure of one atmosphere, since most people live at approximately that pressure. Nevertheless, even on earth the pressure of the atmosphere varies appreciatively, particularly with altitude: and it was realized as early as 1885, as a result of the work of W. Ferrel (5, 6), that the relationship between humidity and wet- and dry-bulb temperatures was a function of pressure. Mr. Ferrel made measurements at sea level and at the top of Pike's Peak in Colorado, where the pressure is only 0.6 that at sea level, and derived a remarkably accurate equation giving the relationship between pressure, wet- and dry-bulb temperatures and partial pressure of water vapor in the air. Brooks and Allen (3) later made measurements from 0.3 to 1.0 atmosphere pressure, and recently Brown (4) extended the range from 0.14 to 5.20 atmospheres.

Reliable psychrometric data or equations for gases other than air have not been available. Since man is normally an air-breathing animal and psychrometry has been principally concerned with man's comfort, there has been little need for psychrometric properties of gases other than air.

This is no longer the case, for today some men do breath gas mixtures that are radically different from the usual nitrogen-oxygen mixture.

For hundreds of years air-breathing men have explored and worked in the ocean in various types of diving gear, but they have been limited to rather shallow depths because of the narcotic effect of nitrogen, which can cause serious trouble at depths greater than 50 feet. For greater depths (down to 1,000 feet or more) the nitrogen must be replaced by some other gas, and the gas that has proved most practicable is helium.

In recent years, there have been a number of undersea habitats in which men have lived and worked in the ocean at depths up to several hundred feet. The pioneering efforts of Jacques Cousteau with his Conshelfs and the U. S. Navy with Sealabs I and II are well known, but many private organizations have also entered this field. The control of humidity in all of these ventures has proved a serious problem, and part of the difficulty has been due to a lack of knowledge of the psychrometric properties of the helium-water vapor system. Attempts to extrapolate from air-water vapor at one atmosphere to helium-water vapor at several atmospheres have caused lots of trouble.

A knowledge of the psychrometric properties of the helium-water vapor system at the conditions encountered in undersea habitats was badly needed. This investigation was designed to fill that need.

III. THEORY OF THE WET- AND DRY-BULB PSYCHROMETER

Many people have contributed to the theory of the wet- and dry-bulb psychrometer (1, 9, 10, 16), and although there is a difference of opinion as to some of the details of mass and heat transfer, the following seems to represent the facts:

> When liquid water is brought into contact with a gas that is not saturated with water vapor, the water will evaporate. This requires latent heat of vaporization, and the temperature of the wetted bulb drops as heat is removed. However, as the temperature of the wetted bulb drops, two things happen: (1) the rate of evaporation decreases as the wetted bulb gets colder, and (2) as soon as the temperature of the wetted bulb gets lower than that of the gas, heat begins to flow from the gas to the bulb, and the rate of heat flow keeps increasing as the temperature of the wetted surface keeps dropping. Eventually the rate at which heat flows from the gas to the bulb becomes equal to the rate at which heat is lost through latent heat of vaporization, and the temperature of the wetted bulb drops no further.

If the quantity of gas is so large compared to the quantity of water that the temperature and humidity of the gas do not change appreciably and if the velocity of the gas over the wetted surface is above a certain minimum value, the lowest temperature reached by the wetted bulb is called the "<u>wet-bulb temperature</u>". The conditions are illustrated in Figure 1.

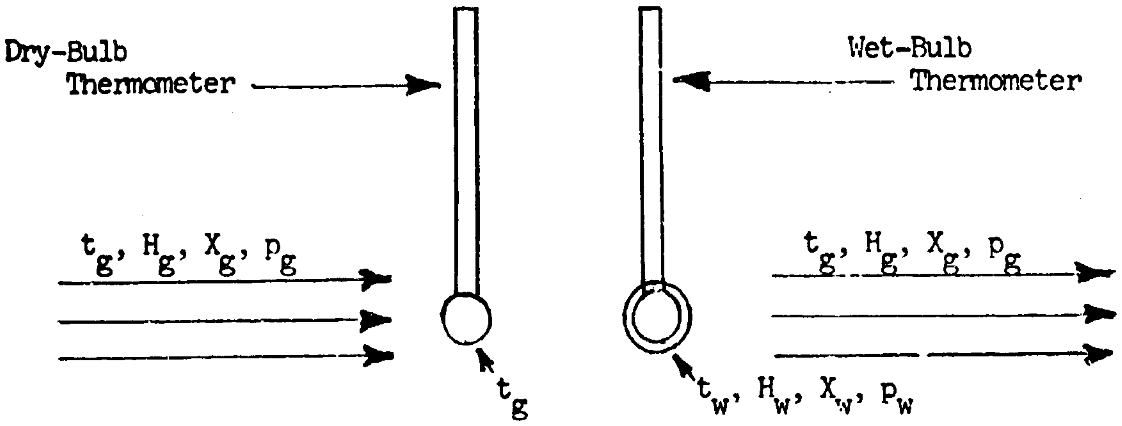


Fig. 1. Sketch to Illustrate Wet-Bulb Temperature.

A gas with temperature t_g, humidity H_g, mole fraction of water vapor X_g and partial pressure of water vapor p_g is passed over two thermometers, one of which is covered with a wetted wick of area A. The quantity of gas is so great that its temperature and humidity do not change appreciably as it passes over the wetted wick. The wick reaches a temperature of t_w, and saturated gas in contact with the wick has a humidity H_w, a mole fraction of water vapor X_w, and a partial pressure of water vapor p_w.

At the wet-bulb temperature, the rate at which heat is transferred from the gas to the wetted bulb is

$$Q/\theta = hA(t_g - t_w) \qquad (1)$$

and the rate at which water is transferred from the bulb to the gas is

$$N_w/\theta = kA(X_w - X_g) \qquad (2)$$

In these equations

Q/θ = heat transferred, B.t.u./hr.

h = heat-transfer coefficient, B.t.u./(hr. x sq.ft. x $^{\circ}$F).

A = area, sq.ft.

t_g = dry-bulb temperature (temperature of the gas), $^{\circ}$F.

t_w = wet-bulb temperature, $^{\circ}$F.

N_w/θ = rate of water evaporation, lb.-mole/hr.

k = mass transfer coefficient, lb.-mole/(hr. x sq.ft. x unit mole fraction difference).

X_w = mole fraction of water vapor in saturated gas at the wet-bulb temperature

X_g = mole fraction of water vapor in the gas stream.

The lb.-moles of water evaporated per hour multiplied by the molal latent heat of vaporization is equal to the B.t.u./hr. of heat transferred. Therefore

$$Q/\theta = hA(t_g - t_w) = (N_w/\theta)(18.016\lambda_w) = kA(18.016\lambda_w)(X_w - X_g) \qquad (3)$$

where

λ_w = latent heat of vaporization of water at the wet-bulb temperature, B.t.u./lb.

18.016 = molecular weight of water.

From Equation 3

$$X_w - X_g = \frac{h}{18.016k\lambda_w}(t_g - t_w) \qquad (4)$$

However

$$X_w = p_w/P \tag{5}$$

$$X_g = p_g/P \tag{6}$$

where

p_w = partial pressure of water vapor in gas saturated at the wet-bulb temperature. (This is equal to the vapor pressure of water at the wet-bulb temperature.)

p_g = partial pressure of water vapor in the gas stream.

P = total pressure.

Substituting in Equation (4) gives

$$p_w - p_g = \frac{h}{18.016k\lambda_w} P(t_g - t_w) \tag{7}$$

or

$$p_w - p_g = KP \frac{(t_g - t_w)}{\lambda_w} \tag{8}$$

where

$$K = \frac{h}{18.016k} \tag{9}$$

The latent heat of vaporization of water can be expressed by the equation

$$\lambda_w = 1093.8 - 0.576t_w \tag{10}$$

Upon substitution of this expression, Equation 8 becomes

$$p_w - p_g = KP \frac{(t_g - t_w)}{1093.8 - 0.576t_w} \tag{11}$$

On the basis of scattered data over a narrow pressure range (from 0.3 to 1.0 atm.) in the literature, Zimmerman and Lavine (17) calculated the value of K for the air-water vapor system to be 0.3895. Later Brown (4) found K to be constant over the range of pressures he investigated (0.14 to 5.20 atm.) and to have a value of 0.397 ± 0.20; and in the present investigation a value of 0.392 was determined.

According to Equation 9 , the psychrometric constant K is a function of the heat and mass transfer coefficients and the molecular weight of the liquid. (The previous discussion referred to "water" and "water vapor" since water is the usual liquid we are interested in, but the analysis applies equally well to any gas-liquid system.)

If we could calculate heat and mass transfer coefficients with sufficient accuracy there would be no need to determine psychrometric data experimentally, except to check the validity of the equation. However, we don't know enough yet about the actual mechanism of heat and mass transfer in the systems to permit us to make calculations of sufficient accuracy.

Calculations for the air-water system indicated that the constant was between 0.34 and 0.40. This was reasonably good since the experimentally determined constant is approximately 0.39. For the helium-water system, however, calculations indicated that the constant was betweer 0.28 and 2.1 — a range much too great to be of any help.

Because we can't calculate the constant, we must determine it experimentally. In fact, the psychrometer is an excellent device for determining mass transfer coefficients from heat-transfer data.

If the constant K is known for a particular system, the partial pressure of vapor in the gas stream can be calculated, and this in turn can be used to calculate the absolute humidity (pounds or moles of vapor per pound or mole of vapor-free gas) or the relative humidity (ratio of partial pressure of vapor in the gas to partial pressure at saturation).

Using ideal gas laws, which are sufficiently accurate for most purposes:

$$H_g = \left[\frac{p_g}{P-p_g}\right]\left[\frac{\text{mole wt. of liquid}}{\text{mole wt. of gas}}\right] \qquad (12)$$

$$H_w = \left[\frac{p_w}{P-p_w}\right]\left[\frac{\text{mole wt. of liquid}}{\text{mole wt. of gas}}\right] \qquad (13)$$

$$RH = \frac{p_g}{p_s} \times 100 \qquad (14)$$

where

H_g = humidity of the gas stream, lb. vapor/lb. vapor-free gas.

H_w = humidity of gas saturated at the wet-bulb temperature, lb. vapor/lb. vapor-free gas.

RH = percent relative humidity.

p_s = partial pressure of vapor in saturated vapor-gas mixture at the dry-bulb temperature. (This is equal to the vapor pressure of the liquid at t_g).

Over the usual atmospheric temperature range, p_g and p_w are small compared to the total pressure, P; and for the air-water system Equations 12 and 13 can be reduced to the approximate equations

$$H_g = \left[\frac{18.016}{28.967}\right]\left[\frac{p_g}{P}\right] \qquad (15)$$

and

$$H_w = \left[\frac{18.016}{28.967}\right]\left[\frac{p_w}{P}\right] \qquad (16)$$

where

28.967 = molecular weight of dry air.

Substituting Equations 15 and 16 into Equation 7 gives

$$(H_w-H_g)\left[\frac{28.967}{18.016}\right] = \left[\frac{h}{18.016k\lambda_w}\right](t_g-t_w) \qquad (17)$$

or

or

$$H_w - H_g = \frac{K'}{\lambda_w} (t_g - t_w) \qquad (18)$$

where

$$K' = \frac{h}{28.967k} \qquad (19)$$

For the air-water system, it has been found experimentally that $K' = 0.26$. Therefore, the common relationship for air-water vapor for the usual atmospheric conditions is

$$H_w - H_g = \frac{0.26}{\lambda_w} (t_g - t_w) \qquad (20)$$

It must always be kept in mind, however, that: (1) Equation 20 is only an approximate equation and that it becomes more and more inaccurate as the temperature is raised, and (2) that it only applies to the air-water system.

IV. WET-BULB TEMPERATURE vs. ADIABATIC SATURATION TEMPERATURE

As pointed out earlier, wet- and dry-bulb psychrometry is based on bringing a large quantity of gas into contact with a limited quantity of liquid. Under these conditions neither the temperature nor the humidity of the gas is changed. A related phenomenon is based on bringing a limited quantity of gas into contact with a large quantity of liquid. Under these conditions, the gas (unless it is already saturated with vapor) will increase in humidity and decrease in temperature. If the system is isolated so that it can neither lose nor gain heat, the temperature reached by the water is known as the "adiabatic-saturation temperature". And, if the system is large enough the gas will leave the chamber saturated with vapor at the adiabatic-saturation temperature. A common example of this process is the humidification of air by passing it through sprays of circulating water.

The wet-bulb temperature is something quite different from the adiabatic-saturation temperature: the former is based on heat and mass transfer while the latter depends only on a simple heat balance, as shown below (and with the aid of Figure 2) for the air-water system.

A heat balance over the system shown in Figure 2, based on t_s as the datum temperature, gives

$$G(0.24)(t_{g1}-t_s) + GH_1(0.48)(t_{g1}-t_s) + GH_1\lambda_s = G(0.24)(t_{g2}-t_s) + GH_2(0.48)(t_{g2}-t_s) + GH_2\lambda_s \qquad (21)$$

where:

G = lb. dry air/hr.

t_{g1} = initial temperature of the air, $^{\circ}$F.

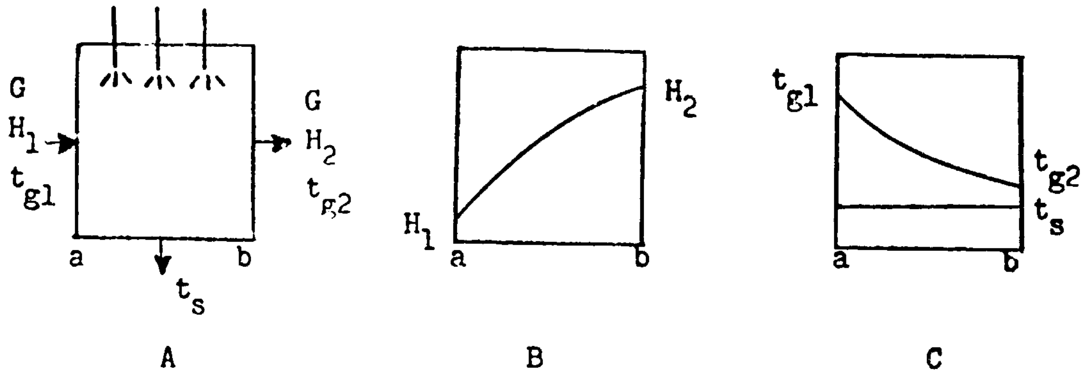


Fig. 2. Sketches to Illustrate Adiabatic Saturation.

(A) Spray chamber in which a quantity of air, G, with a temperature of t_g and a humidity of H_1 is passed through sprays of circulating water whose temperature reaches t_s. The air leaves with a humidity of H_2. (B) and (C) show, respectively, the changes in humidity and temperature as the air passes through the chamber.

t_{g2} = final temperature of the air, °F.

t_s = adiabatic saturation temperature (temperature of the water), °F.

H_1 = initial humidity of the air, lb. water/lb. dry air.

H_2 = final humidity of the air, lb. water/lb. dry air.

λ_s = latent heat of vaporization of water at t_s, B.t.u./lb.

0.24 = specific heat of dry air, B.t.u./(lb. x °F).

0.48 = specific heat of water vapor, B.t.u./(lb. x °F).

If the air leaves the chamber saturated with water vapor (the usual condition) t_{g2} becomes t_s, H_2 becomes H_s (the humidity at saturation), and Equation 21 reduces to

$$G(0.24)(t_{g1}-t_s) + GH_1(0.48)(t_{g1}-t_s) + GH_1\lambda_s = GH_s\lambda_s \qquad (22)$$

or

$$(0.24)(t_{g1}-t_s) + H_1(0.48)(t_{g1}-t_s) = (H_s-H_1)\lambda_s \qquad (23)$$

or

$$H_s - H_1 = \frac{(0.24 + 0.48H_1)(t_{g1}-t_s)}{\lambda_s} \qquad (24)$$

Under the usual atmospheric conditions, the quantity $(0.24 + 0.48H_1)$ is very nearly equal to 0.26. For example, at 70°F. and 50% saturation, $H_1 = 0.0079$, and $0.24 + 0.48H_1 = 0.24 + 0.0079(0.48) = 0.244$; and at 100°F and 80% saturation, $H_1 = 0.0345$, and $0.24 + 0.48H_1 = 0.24 + 0.0345(0.48) = 0.257$.

Therefore, under these conditions Equation 24 becomes practically equal to Equation 20, and the adiabatic saturation temperature becomes substantially the same as the wet-bulb temperature.

This, however, is a mere coincidence, and a very unfortunate coincidence, for it has led to a common, but eroneous, belief that adiabatic-saturation and wet-bulb equations and charts can be used interchangeably. Actually, they can be used interchangeably for the air-water system if the temperatures are not very high and the highest accuracy is not required.

However, for systems other than air and water, this coincidence does not occur, and widely different results are obtained from the two equations even at low temperatures. For example, if adiabatic-saturation temperatures are calculated for the helium-water system and then used as wet-bulb temperatures the results are worthless. And even for the air-water system it is not wise to use the equations interchangeably at temperatures much above 125°F.

V. APPARATUS

An apparatus for determining the value of the constant K in the psychrometric equation consists of the following elements: (1) a system for preparing and delivering a gas stream of the desired temperature, pressure, and humidity; (2) instruments for determining the amount of water vapor in the gas stream, the gas flow rate, and the pressure; and (3) a psychrometer consisting of wet- and dry-bulb measuring devices with appropriate means for feeding water to the wet bulb.

The apparatus finally used is shown diagramatically in Figure 3. Most of the system presented few problems, but the psychrometer, itself, required a great deal of study before a reliable unit was developed.

Gas Preparation and Delivery System

The gas preparation and delivery system (Figure 4) includes a pressure regulator, humidification column, entrainment separator, electrical heating tapes, and a series of needle valves to portion the flow. The various parts of the system are connected with 3/8" o.d., 0.032" wall-thickness, standard, soft, copper, refrigeration tubing connected with compression-type fittings. All components can withstand pressures of at least 400 psi. The line pressure, and resulting flow rate, is kept constant with a diaphragm-type flow regulator.

As can be seen from Figure 4, gas from a cylinder is split into two streams, one of which is passed through a humidification column after which it is recombined with the other stream. By regulating the temperature of the humidification column and the ratio of the two gas flow rates,

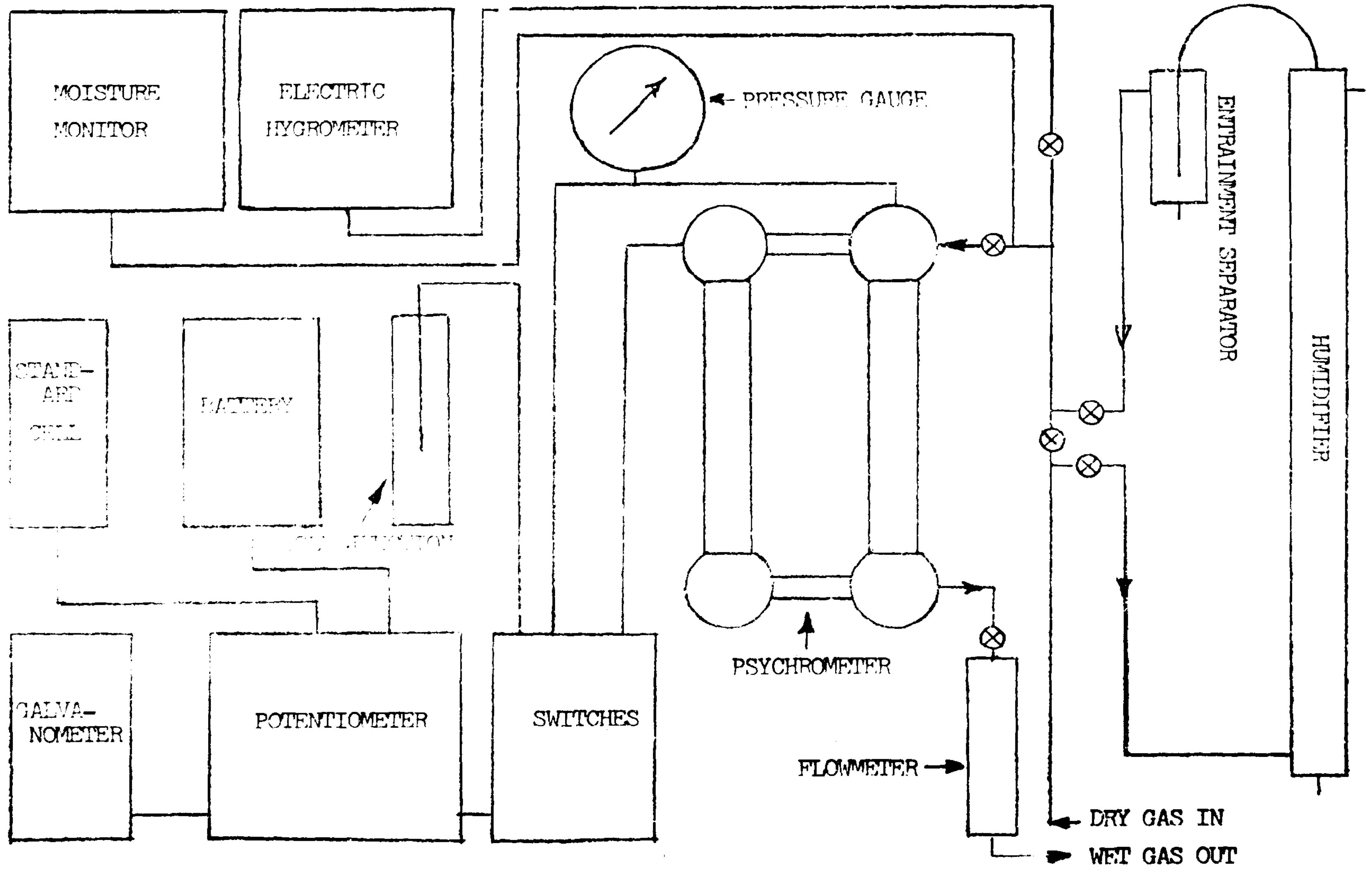


Fig. 3 Diagram of Apparatus

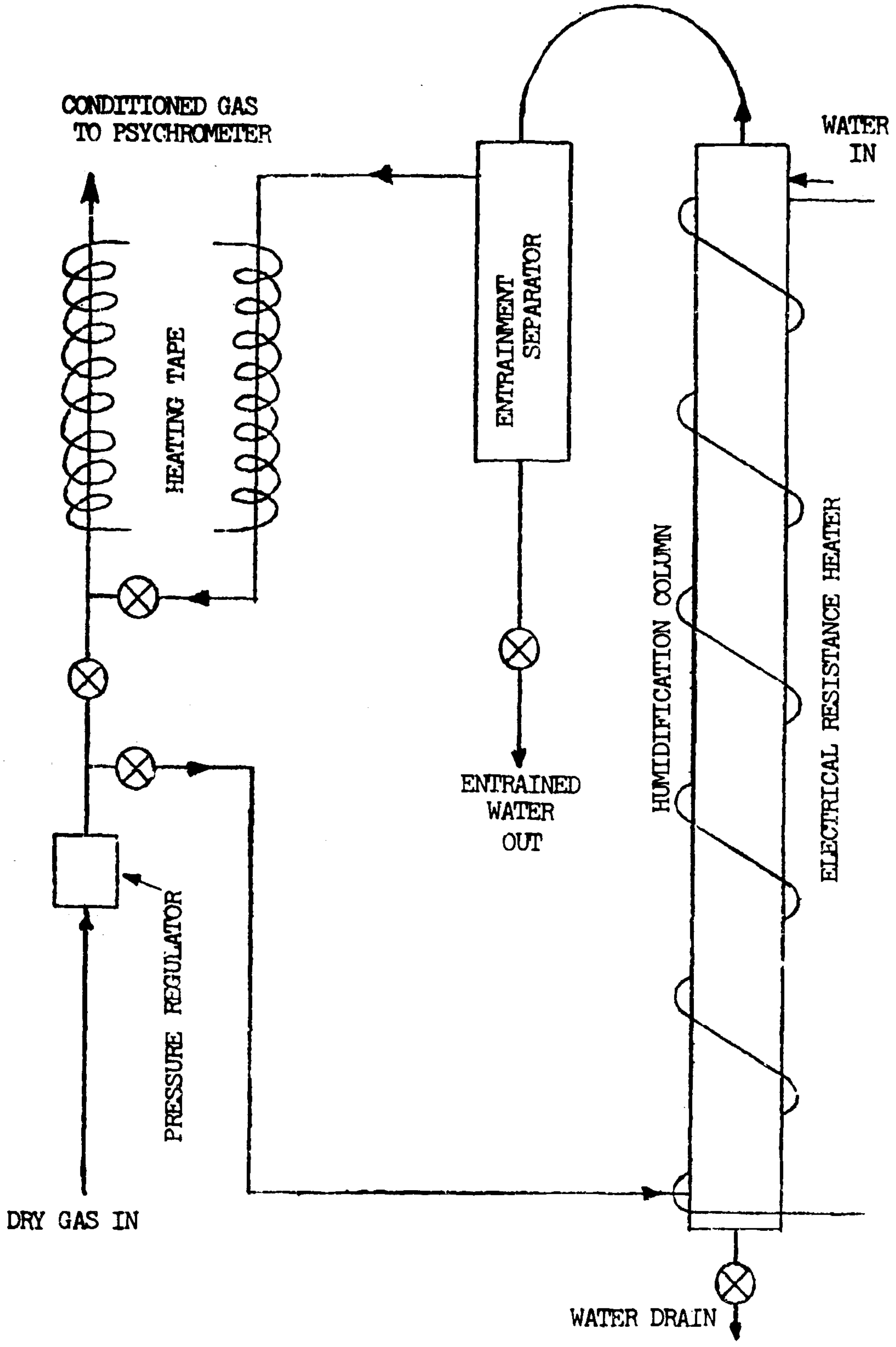


Fig. 4. Gas Humidification System

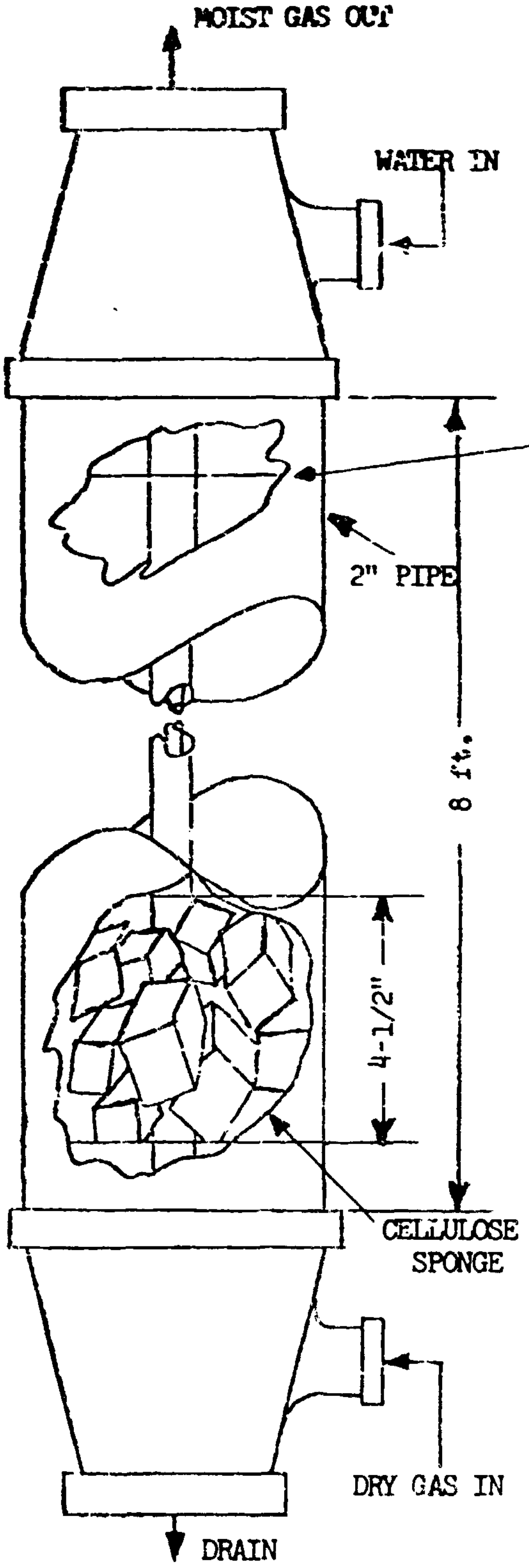
a final gas stream of any desired humidity can be readily obtained.

To eliminate the need for a circulating pump, the batch-type humidification column shown in Figure 5 was designed, and it proved to be very satisfactory. It consists of an 8-foot length of 2-inch nominal diameter, schedule 40 steel pipe, packed with one-half inch cubes of cellulose sponge to a height of 7¼ feet. The packed section is divided into nineteen 4½-inch sections of sponges separated by discs of 20-mesh stainless steel screen. This construction keeps the sponges from packing together in the bottom of the column after they are wetted. In operation, water is introduced into the top of the column, with no gas flowing, until the sponges absorb all of the water they can. The wet packing holds 2.2 lb. of water, and has a void fraction of 0.429. This quantity of water is sufficient to supply 6 standard cu.ft. per minute of saturated gas at 100°F. and 20 psig for 2.7 hr. starting with dry helium.

The column is wrapped with a 1,200-watt heating tape, and other heating tapes are wrapped around the delivery piping. Variable transformers are used to control temperatures.

An entrainment separator, Figure 6, effectively prevents the carry over of liquid water.

With this apparatus, the gas leaving the system is discarded to the atmosphere. Originally, the system was designed so that discharged gas could be collected in a balloon and pumped back into cylinders. Unfortunately, the only compressor available had insufficient capacity and proved unsatisfactory.



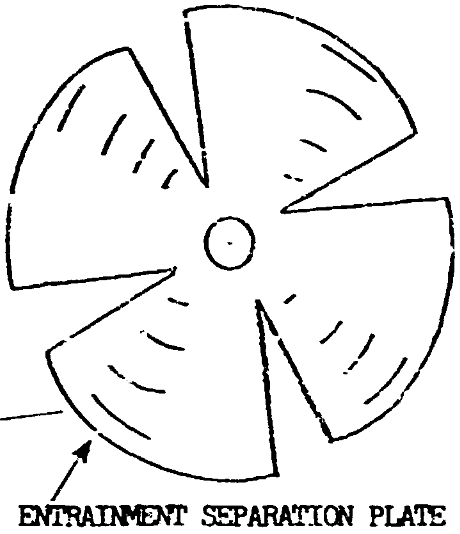


Fig. 5. Humidification Column

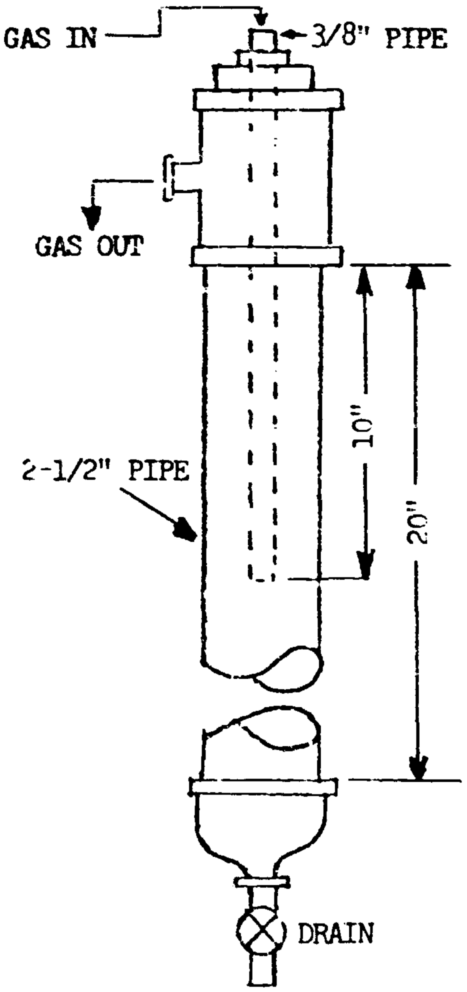


Fig. 6. Entrainment Separator

Measuring System

Measurements are made of the following quantities: wet- and dry-bulb temperatures, pressure, flow rate, and humidity. Temperatures are measured by means of copper-constantan thermocouples and a Leeds and Northrup Type K-3 potentiometer. Pressures up to a little more than 1 atm. gauge are measured with a mercury manometer. For higher pressures, a Heise bourdon tube pressure gauge, reading to 0.2 psi gauge, is used. Atmospheric pressure is measured with a Taylor aneroid barometer. Gas flow is measured with a Brooks Full-View Rotameter.

For humidity measurements, two instruments are used: a Moisture Monitor from Consolidated Electrodynamics Corporation and an Electric Hygrometer from Hygrodynamics Incorporated. The former, which indicates humidity in parts per million by volume at 25°C. and one atmosphere, works best below 3,000 parts per million. The electric hygrometer, which uses a dew point sensor, indicates relative humidity at atmospheric pressure and room temperature. It works best above 7% relative humidity.

The Psychrometer

The design of a psychrometer for helium presents certain problems that are not of great importance in a psychrometer for air, just as a psychrometer for pressure operation presents problems not present in a psychrometer for atmospheric pressure. Helium is expensive. Its density is so low that it takes several times the quantity of helium by volume as of air to obtain sufficient velocity for a true wet-bulb temperature reading. Thermal conductivities and heat-transfer coefficients of helium are much greater than those of air, and water evaporates into helium much faster than into air. All of these factors make it desirable to construct a psychrometer for helium as small as practicable.

At first, a psychrometer was constructed using 3/8" o.d. copper tubing and fittings and a wet-bulb thermocouple with the bead covered by a cloth wick which extended into a well filled with water. The results obtained with this apparatus using, air, nitrogen, and helium were very inconsistent and did not agree with results obtained with apparatus of larger internal diameter.

After many experiments it was found that the original apparatus had several faults: (1) the diameter of the wick was so large compared to the internal cross section of the 3/8" tubing that the free cross sectional area was not great enough to give a proper flow pattern; (2) the water evaporated so rapidly that the wick could not be kept properly wetted; (3) the pressure tap was located at some distance from the wet-bulb thermocouple, and it was not certain that the measured pressure was the true pressure at the wet-bulb thermocouple; and (4) heat conductivity along the thermocouple resulted in a wet-bulb reading that was higher than the true wet-bulb temperature.

The apparatus shown in Figure 7 eliminated all of the difficulties and gave reproducible results which were consistent with those obtained in other apparatus.

This apparatus, which was made from 5/8" o.d., approx. 7/16" i.d. water gauge glass (A and B) and fittings, has a number of significant features: Both the wet- and dry-bulb thermocouples (C and D) are made from 30-gauge, fiberglass-covered, copper-constantan wire and are mounted in fine glass capillary tubes (E and F) made by softening and drawing out thin-walled glass tubing. The capillary tubes are attached to the brass fittings with epoxy cement. The wet-bulb thermocouple is covered from

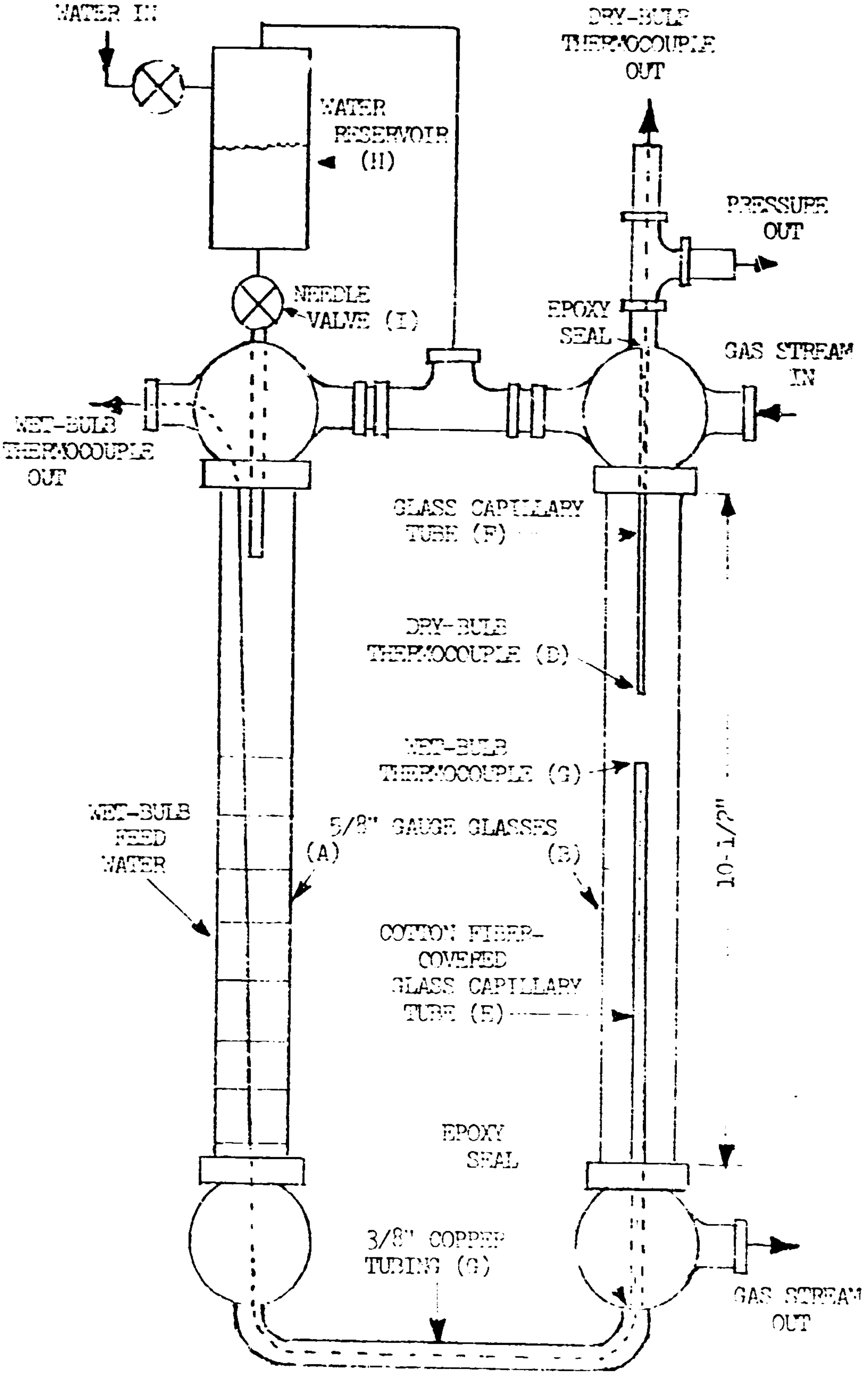


Fig. 7 Details of Psychrometer

its tip to the bottom of the gauge glass with a thin sheet of cotton fibers; and the total diameter of the unit is slightly greater than one-tenth of an inch. The wet-bulb thermocouple is passed through the cotton fiber-covered capillary tube, through the copper tubing (G) connecting the two sections of gauge glass, and out the top of the feed-water gauge glass. The glass capillary tube (F) through which the dry-bulb thermocouple is passed, is connected directly to the pressure-measuring system. Thus, the measured pressure is actually the pressure at the tip of the dry-bulb thermocouple.

During operation, water is fed to the system continually from reservoir (H) through control valve (I) into gauge glass (A) at a rate sufficient to maintain a level that gives the desired flow to the wet bulb. The water flows through the copper tubing (G) and capillary tube (F), out of the top of the capillary tube, and down the outside of the cotton fiber-covered capillary. The rate of flow is controlled so that the fibers are kept covered with water throughout their entire length but without excess water dripping off. However, it was found that there could be a considerable variation in water flow without affecting the wet-bulb temperature reading.

The water flowing down the fiber-covered surface is cooled by evaporation as the gas passes over it. This, in turn, cools the water rising through the capillary tube. As a result, the water is cooled to practically the wet-bulb temperature before it reaches the thermocouple bead, which is covered at all times by a thin film of water. Furthermore, since the thermocouple wire and glass capillary are cooled to the wet-bulb temperature over an appreciable length, there is no conduction of heat away from the thermocouple bead.

VI. VELOCITY OF GAS OVER THE WET BULB

It has been observed (1, 3, 4) that as the velocity of the gas stream increases the temperature of the wet bulb decreases to a certain minimum value which is independent of further increase in velocity. This constant value is the true wet-bulb temperature. Therefore, in using a wet- and dry-bulb psychrometer it is essential that the gas velocity be high enough. For the air-water system at 1-atm. pressure, the accepted minimum required velocity is 600 ft. per min.

For any given gas-liquid system, the minimum required linear velocity decreases with pressure. Brooks and Allen (3) reported that this minimum velocity varies inversely as the square root of the pressure, but Brown (4), who worked over a much greater pressure range than Brooks and Allen, found that the minimum required linear velocity varied inversely with pressure and, therefore, the minimum required mass velocity remained constant. For the air-water system he found the value to be 2,800 lb./(hr. x sq.ft.), and in his subsequent experimental work he used a mass velocity of 3,000 lb./(hr. x sq.ft.) to have a margin of safety.

Harrison (9) and Kusuda (10), however, claimed that Reynolds number, DG/μ, is the true parameter. Nevertheless, even if this is correct, for a given system the diameter, D, is constant and the viscosity of the gas, μ, is essentially independent of pressure at constant temperature. Therefore, the mass velocity, G, like Reynolds number, will remain constant as the pressure is varied. Furthermore, viscosities of gases do not vary much over the ordinary range of atmospheric temperature; and whether a minimum mass velocity or a minimum Reynolds number is maintained is immaterial

In the present investigation the minimum mass velocity for air and for helium was found to be approximately 3,500 lb./(hr. x sq.ft.). This corresponds to a Reynolds number of approximately 2,200; and this minimum value was maintained in all subsequent work with helium.

It is interesting to note that the minimum Reynolds number for accurate wet-bulb temperature readings corresponds to the transition from viscous to turbulent flow. Therefore, it seems that to insure an accurate wet-bulb temperature reading the gas flow must be turbulent.

In the case of helium, a mass flow rate of 3,500 lb./(hr. x sq.ft.) corresponds to a linear velocity at 70°F. and 1 atm. of

$$\frac{(3.500)(359)(460 + 70)}{(60)(4.003)(492)} = 5{,}636 \text{ ft./min.}$$

or

$$\frac{(5{,}636)(60)}{5{,}280} = 64 \text{ miles/hr.}$$

This extremely high velocity emphasizes one of the great difficulties in obtaining accurate wet-bulb temperatures with helium.

VII. RESULTS

Table 1 is a summary of results obtained with helium using the apparatus as finally developed. Actually, a few hundred other measurements were made and many of the calculated values of K agreed very closely with those in Table 1, but these results are not shown because of doubt as to their accuracy.

The percentage figures in the last column are overall maximum errors that would result from maximum errors or uncertainties in all measurements, assuming that they all acted in the same direction.

The arithmetic average of the 23 values of K is 0.470. Other average values are as follows:

14 runs with wet gas, K = 0.476

9 runs with dry gas, K = 0.460

7 runs using Electric Hygrometer, K = 0.484

7 runs using Moisture Monitor, K = 0.467

With a value of K = 0.470, the psychrometric equation for the helium-water system is:

$$p_w - p_g = \frac{0.470\ P(t_g - t_w)}{1093.8 - 0.576t_w} \qquad (25)$$

Table 1
Summary of Data and Results of Determination of Psychrometric Constant

Run No.	Pressure, " Hg			Temperature, °F.			Relative humidity, %		Hygrometer used*	K	Range
	gauge, P_b	atmospheric P_a	total P	dry bulb t_g	wet bulb t_w	at hygrometer t_a	at P_a	at P			
1	51.31	30.16	81.47	82.20	71.86	87.0	37.5	11.90	EH	0.464	± 16%
2	51.31	30.16	81.47	82.20	71.86	87.0	36.8	11.90	MM	0.474	± 12%
3	51.31	30.16	81.87	82.40	72.01	87.0	37.3	11.85	EH	0.464	± 17%
4	51.31	30.16	81.87	82.40	72.01	87.0	37.4	11.85	MM	0.462	± 14%
5	51.36	30.16	81.87	82.66	72.03	87.0	36.2	11.60	EH	0.465	± 16%
6	51.36	30.16	81.87	82.66	72.03	87.0	37.1	11.60	MM	0.453	± 13%
7	48.86	30.16	79.02	82.82	71.99	87.0	35.6	11.90	EH	0.476	± 15%
8	48.86	30.16	79.02	82.82	71.99	87.0	36.3	11.90	MM	0.467	± 12%
9	89.58	30.41	119.99	79.16	71.24	82.5	31.2	7.10	EH	0.506	± 16%
10	89.58	30.41	119.99	79.16	71.24	82.5	31.9	7.10	MM	0.499	± 5%
11	91.21	30.41	121.62	79.38	71.57	83.0	31.9	7.10	EH	0.507	± 17%
12	91.21	30.41	121.62	79.38	71.57	83.0	35.4	7.10	MM	0.468	± 6%
13	91.21	30.41	121.62	79.62	71.76	83.0	31.7	7.10	EH	0.508	± 16%
14	91.21	30.41	121.62	79.62	71.76	83.0	37.0	7.10	MM	0.499	± 6%
15	52.53	30.14	82.67	82.84	65.30	—	0	0	—	0.458	±0.8%
16	51.92	30.14	82.06	83.19	65.37	—	0	0	—	0.455	±0.8%
17	51.51	30.14	81.65	83.59	65.57	—	0	0	—	0.456	±0.8%
18	89.58	30.41	119.99	80.00	67.22	—	0	0	—	0.463	±0.8%
19	91.21	30.41	121.62	80.26	67.42	—	0	0	—	0.457	±0.8%
20	91.62	30.41	122.03	80.37	67.61	—	0	0	—	0.461	±0.8%
21	91.62	30.41	122.03	80.37	67.61	—	0	0	—	0.461	±0.8%
22	210.32	30.41	240.73	80.34	72.65	—	0	0	—	0.460	±0.8%
23	162.07	30.41	192.48	80.03	71.12	—	0	0	—	0.472	±0.8%

* EH = Electric Hygrometer; MM = Moisture Monitor.

VIII. ANALYSIS OF ERRORS

In order to calculate the probable accuracy of the final result, it was first necessary to estimate the maximum error in each measurement. In the case of instruments, this was based on manufacturers' statements.

The maximum errors in measurements are:

Temperature:

1. t_w (wet-bulb temperature), ±0.02°F.
2. t_g (dry-bulb temperature), ±0.02°F.
3. t_a (temperature at which humidity is measured, ±0.05°F.

Pressure:

1. P_b (bourdon gauge pressure), ±0.2 psi = ±0.4" Hg
2. P_a (atmospheric pressure), ±0.04" Hg

Humidity:

1. Using Electric Hygrometer, ±1.5% RH (relative humidity)
2. Using Moisture Monitor:
   a. Below 3,000 ppm., ±150 ppm. (parts per million by volume)
   b. Above 3,000 ppm., ±500 ppm.

The maximum error in p_w (partial pressure of water vapor in gas saturated at t_w = vapor pressure of water at t_w) depends upon the maximum error in t_w.

The maximum error in p_g (partial pressure of water vapor in the gas stream) depends upon the accuracy of the measurements of t_a, P_b, P_a, and RH or ppm., for

$$\frac{p_a}{p_{sat.}} = \frac{RH}{100} \qquad (26)$$

where

p_a = partial pressure of water vapor in gas measured at t_a and P_a.

$p_{sat.}$ = vapor pressure of water at t_a.

RH = percent relative humidity measured at t_a and P_a.

and

$$p_g = \left[\frac{p_a}{P_a}\right] (P) = \left[\frac{RH}{100}\right]\left[\frac{p_{sat.}}{P_a}\right](P_b + P_a) \tag{27}$$

or

$$p_g = \left[\frac{ppm.}{1,000,000}\right] (P) = \left[\frac{ppm.}{1,000,000}\right](P_b + P_a) \tag{28}$$

Equation 11 can be written as

$$K = \frac{(p_w - p_g)(1093.8 - 0.576t_w)}{P(t_g - t_w)} \tag{29}$$

This equation was used to calculate the value of K assuming: (1) no errors in the measured quantities, (2) that all errors are in the direction that will give a maximum value of K, and (3) that all errors are in the direction that will give a minimum value of K.

To illustrate these calculations, the data for Run No. 1 Table 1 were used:

$t_w = 71.86 \pm 0.02^{\circ}F.$

$t_g = 82.20 \pm 0.02^{\circ}F.$

$t_a = 87.0 \pm 0.05^{\circ}F.$

$P_a = 30.16 \pm 0.04''$ Hg

$P_b = 25.20 \pm 0.02$ psi $= 51.31 \pm 0.4''$ Hg

RH $= 11.90 \pm 1.5\%$

From these measurements, and assuming no error

$p_w = 0.78726''$ Hg

$p_{sat.} = 1.2931" \text{ Hg}$

$$p_g = (0.1190)\frac{(1.2931)(51.31 + 30.16)}{(30.16)} = 0.41567" \text{ Hg}$$

and

$$K = \frac{(0.78726 - 0.41567)\ 1093.8 - 0.576(71.86)}{(51.31 + 30.16)(82.20 - 71.86)} = 0.464$$

If the errors are such as to give a maximum value of K, the errors in t_w and P_a are positive and the errors in t_g, t_a, RH, and P_b are negative.

Therefore:

$t_w = 71.88^oF.$

$t_g = 82.18^oF.$

$t_a = 86.95^oF.$

$P_b = 50.91" \text{ Hg}$

$P_a = 30.20" \text{ Hg}$

$RH = 10.4\%$

$p_w = 0.78779" \text{ Hg}$

$p_{sat} = 1.2911" \text{ Hg}$

$$p_g = \frac{(0.104)(1.2911)(50.91 + 30.20)}{30.20} = 0.36063"\text{Hg}$$

Assuming errors for the latent heat term and substituting the appropriate values in Equation 28 gives

$$K = \frac{(0.78779 - 0.36063)\ (1093.8 + 0.05) - (0.576 - 0.0005)(71.88)}{(50.91 + 30.20)(82.18 - 71.88)}$$

$$= 0.538$$

For a minimum value of K, the errors in t_w and P_a are negative, and the errors in t_g, t_a, RH, and P_b are positive.

Under these conditions:

$t_w = 71.84^oF.$

$t_g = 82.22^{\circ}F.$

$t_a = 87.05^{\circ}F.$

$P_b = 51.71''$ Hg

$P_a = 30.12''$ Hg

$RH = 13.4\%$

$p_w = 0.78673''$Hg

$P_{sat.} = 1.2952''$ Hg

$$p_g = \frac{(0.134)(1.2952)(51.71 + 30.12)}{30.12} = 0.47152'' \text{ Hg}$$

and

$$K = \frac{(0.78673 - 0.47152)\left[(1093.8 - 0.05) - (0.576 + 0.0005)(71.84)\right]}{(51.71 + 30.12)(82.22 - 71.84)}$$

$$= 0.391$$

The maximum value of K based on maximum errors is (0.538 - 0.464) x (100)/(0.464) = 16% higher than the value based on no assumed errors; and the minimum value is (0.464 - 0.391)(100)/(0.464) = 16% lower.

It is evident that the greatest error is in the humidity measurement, but to get a better picture of the relative importance of the numerous errors or uncertainties, values of K were calculated assuming only one error at a time.

(1) with $t_w = 71.86 + 0.02 = 71.88^{\circ}F$

$$K = \frac{(0.78779 - 0.41567)\left[1093.8 - 0.576(71.88)\right]}{(51.31 + 30.16)(82.20 - 71.88)} = 0.466$$

(2) with $t_g = 82.20 + 0.02 = 82.22^{\circ}F$

$$K = \frac{(0.78726 - 0.41567)\left[1093.8 - 0.576(71.86)\right]}{(51.31 + 30.16)(82.22 - 71.86)} = 0.465$$

(3) with $t_a = 87.0 + 0.05 = 87.05^{\circ}F$

$$p_g = \frac{(0.1190)(1.2952)(51.31 + 30.16)}{(30.16)} = 0.41634'' \text{ Hg}$$

$$K = \frac{(0.78726 - 0.41634)\left[1093.8 - 0.576(71.86)\right]}{(51.31 + 30.16)(82.20 - 71.86)} = 0.463$$

(4) with $P_b = 51.31 + 0.4 = 51.71'' \text{ Hg}$

$$p_g = (0.1190)\,\frac{(1.2931)(51.71 + 30.16)}{(30.16)} = 0.41771'' \text{ Hg}$$

$$K = \frac{(0.78726 - 0.41771)\left[1093.8 - 0.576(71.86)\right]}{(51.71 + 30.16)(82.20 - 71.86)} = 0.459$$

(5) with $P_a = 30.16 + 0.04 = 30.20'' \text{ Hg}$

$$p_g = (0.1190)\,\frac{(1.2931)(51.31 + 30.20)}{(30.20)} = 0.41532'' \text{ Hg}$$

$$K = \frac{(0.78726 - 0.41532)\left[1093.8 - 0.576(71.86)\right]}{(51.31 + 30.20)(82.20 - 71.86)} = 0.464$$

(6) with $RH = 11.90 + 1.5 = 13.40\%$

$$p_g = (0.1340)\,\frac{(1.2931)(51.31 + 30.16)}{(30.16)} = 0.46806'' \text{ Hg}$$

$$K = \frac{(0.78726 - 0.46806)\left[1093.8 - 0.576(71.86)\right]}{(51.31 + 30.16)(82.20 - 71.86)} = 0.399$$

From these calculations it can be seen that the effect of the uncertainty in each of the variables for Run No. 1 is: t_w, 0.4%; t_g, 0.2% t_a, 0.2%; P_b, 1.1%; P_a, 0; RH, 14.0%.

As was pointed out earlier, the last column of Table 1 shows the maximum error or uncertainty in the various runs based upon maximum assumed errors. Since the largest error is in the humidity measurement, the runs with dry gas, obviously, show very little calculated error. Nevertheless, the actual error might be somewhat greater than indicated because of a possibility that the gas picked up some adsorbed water from the walls of the equipment. The humidity-measuring devices were not sufficiently accurate to measure this, and an estimate would be meaningless. Therefore no attempt was made to account for it in the error analysis.

Although Table 1 shows the maximum errors that might result under the most unfavorable conditions. Table 2 shows that the actual variations from the average are much smaller, as would be expected since the error in any measurement is not likely to be the maximum and the probability is that some errors would cancel others.

The average deviation from the value of K = 0.470 is 0.013, as shown in Table 2. The standard deviation is somewhat higher as a result of the effect of the few points with high deviations.

The standard deviation s(K), is:

$$s(K) = \sqrt{\frac{\Sigma(K - \overline{K})^2}{N - 1}} \tag{30}$$

where N = number of points.

Substituting the appropriate values

$$s(K) = \sqrt{\frac{6955 \times 10^{-6}}{23 - 1}} = 0.0177$$

Therefore, the psychrometric constant for helium is K = 0.470 ± 0.018.

Table 2

Deviations of Psychrometric Constants from Average

Run No.	K	$(K-\bar{K}) \times 10^3$	$(K-\bar{K})^2 \times 10^6$	Deviation from average, %
1	0.464	-6	36	1.3
2	0.474	+4	16	0.9
3	0.464	-6	36	1.3
4	0.462	-8	64	1.7
5	0.465	-5	25	1.1
6	0.453	-17	289	3.7
7	0.476	+6	36	1.3
8	0.467	-3	9	0.6
9	0.506	+36	1296	7.8
10	0.499	+29	841	6.2
11	0.507	+37	1369	8.0
12	0.468	-2	4	0.4
13	0.508	+38	1444	8.2
14	0.449	-21	441	4.5
15	0.458	-12	144	2.6
16	0.455	-15	225	3.2
17	0.456	-14	196	3.0
18	0.463	-7	49	1.5
19	0.457	-13	169	2.8
20	0.461	-9	81	1.9
21	0.461	-9	81	1.9
22	0.460	-10	100	2.2
23	0.472	+2	4	0.4
	Average $K = 0.470$	$(K-\bar{K}) = 309 \times 10^{-3}$	$(K-\bar{K})^2 = 6955 \times 10^{-6}$	

IX. PSYCHROMETRIC CHARTS

Where there is considerable need for psychrometric data, charts have the advantage over equations for they are easier to use and save a great deal of time. Since the reason for measuring wet- and dry-bulb temperatures is to determine the amount of water vapor in a gas, the common type of chart shows relative humidities and absolute humidities (either lb. water vapor/lb. dry gas, or moles water vapor/mole dry gas) as functions of wet- and dry-bulb temperatures. For such a chart, however, the pressure must be held constant. Therefore, a separate chart must be prepared for each desired pressure. The charts are not difficult to prepare, but their preparation can be very time consuming.

The partial pressure of the water vapor in the gas can be calculated from Equation 25

$$p_w - p_g = \frac{0.470P(t_g - t_w)}{1093.80 - 0.576t_w}$$

and the humidity can be calculated from the partial pressure using Equation 12, which, for the helium-water system, becomes

$$H_g = \left[\frac{p_g}{P - p_g}\right]\left[\frac{18.016}{4.003}\right] = 4.501\,\frac{p_g}{P - p_g} \qquad (31)$$

To simplify the preparation of charts a computer program was developed for the I.B.M. 360 and 1620 systems. This program is shown in the Appendix. Figures 8-12 are psychrometric charts for the helium-water system for pressures of 1 atm. (0 ft. sea water), 4 atm. (approx. 90 ft. sea water), 7 atm. (approx. 180 ft. sea water), 10 atm. (approx. 270 ft. sea water), and 21 atm. (approx. 600 ft. sea water). These charts were prepared by computer.

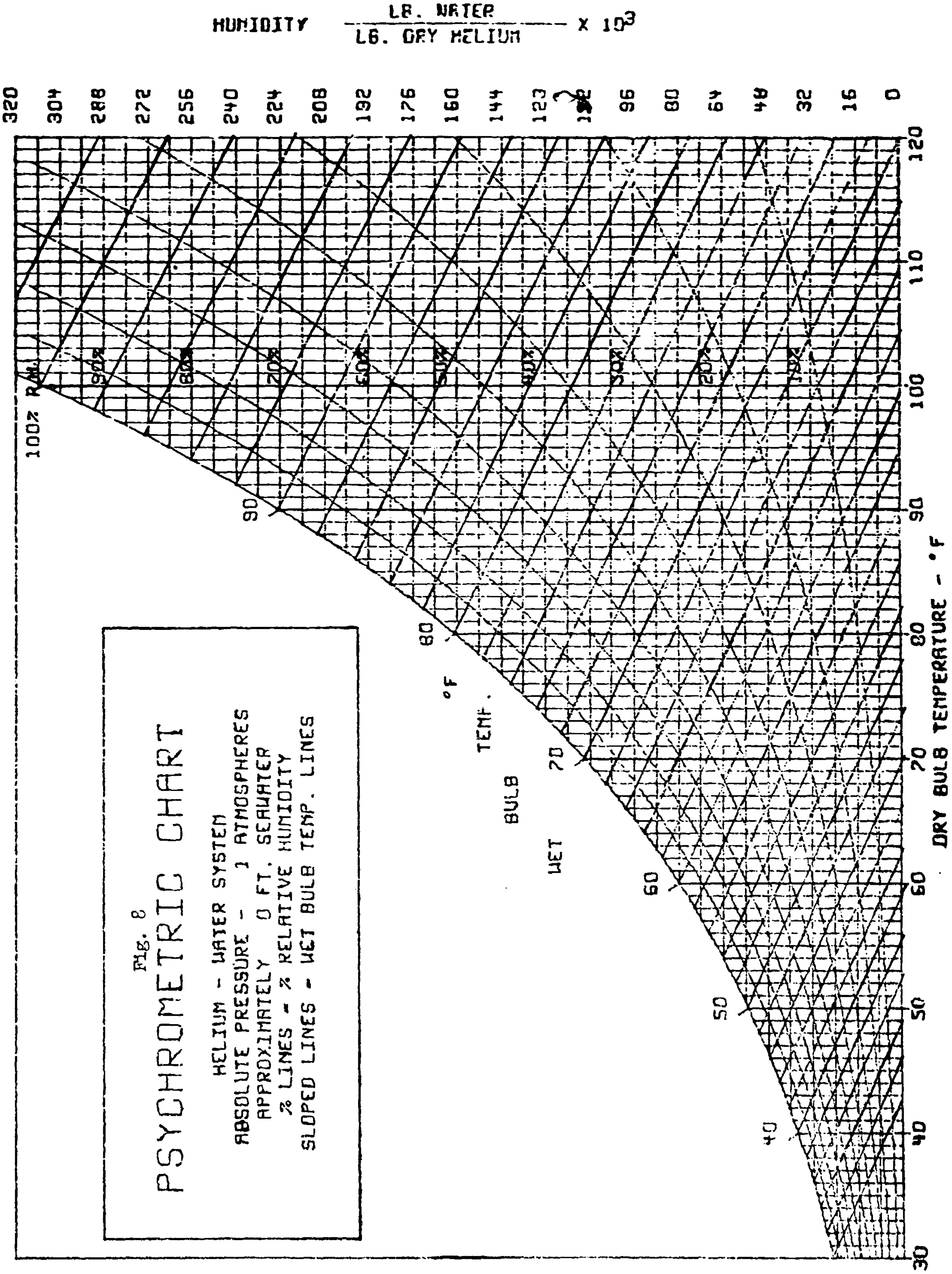


Fig. 8

PSYCHROMETRIC CHART

HELIUM - WATER SYSTEM
ABSOLUTE PRESSURE - 1 ATMOSPHERES
APPROXIMATELY 0 FT. SEAWATER
% LINES - % RELATIVE HUMIDITY
SLOPED LINES - WET BULB TEMP. LINES

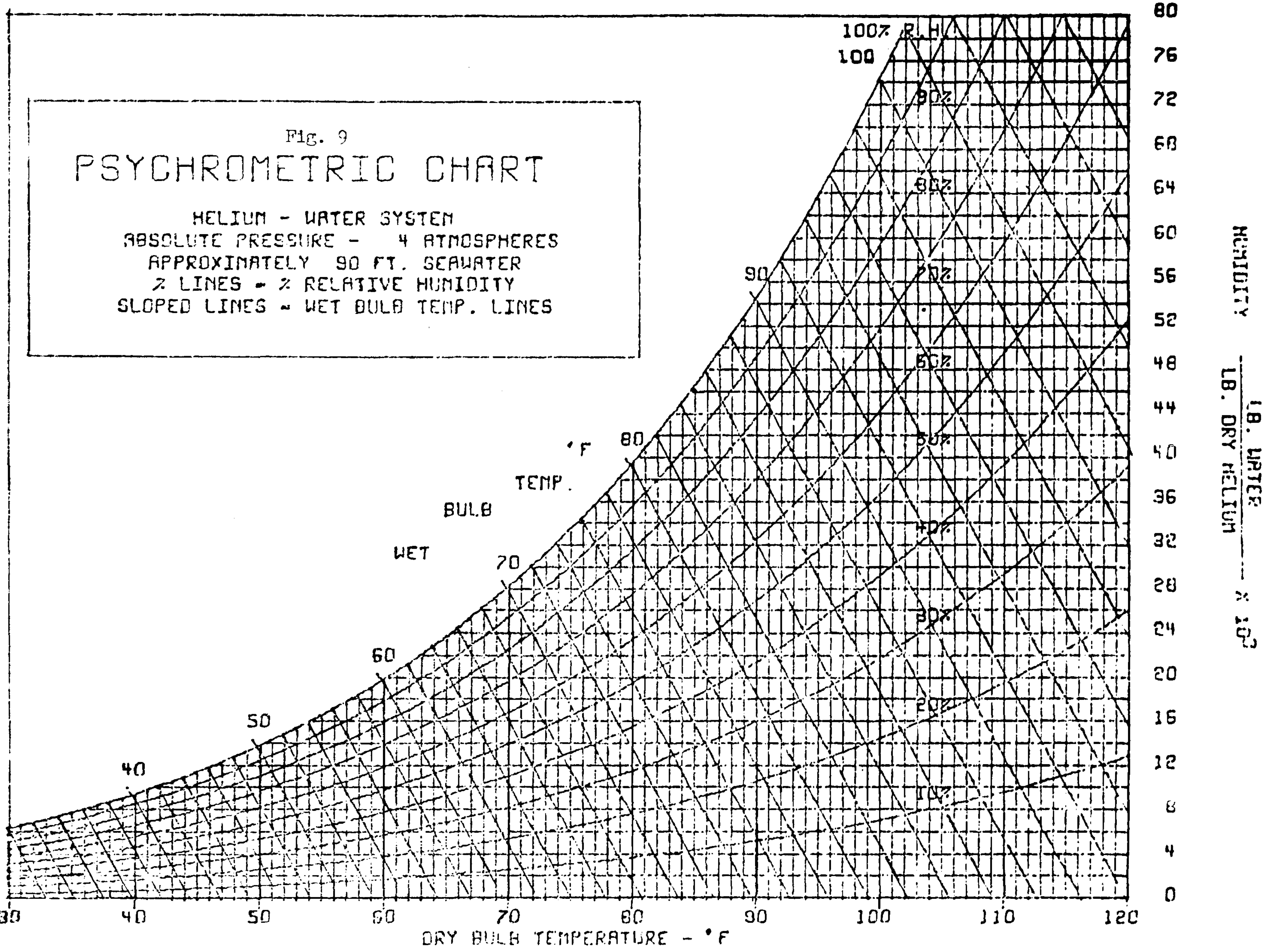


Fig. 9

PSYCHROMETRIC CHART

HELIUM – WATER SYSTEM
ABSOLUTE PRESSURE – 4 ATMOSPHERES
APPROXIMATELY 90 FT. SEAWATER
% LINES – % RELATIVE HUMIDITY
SLOPED LINES – WET BULB TEMP. LINES

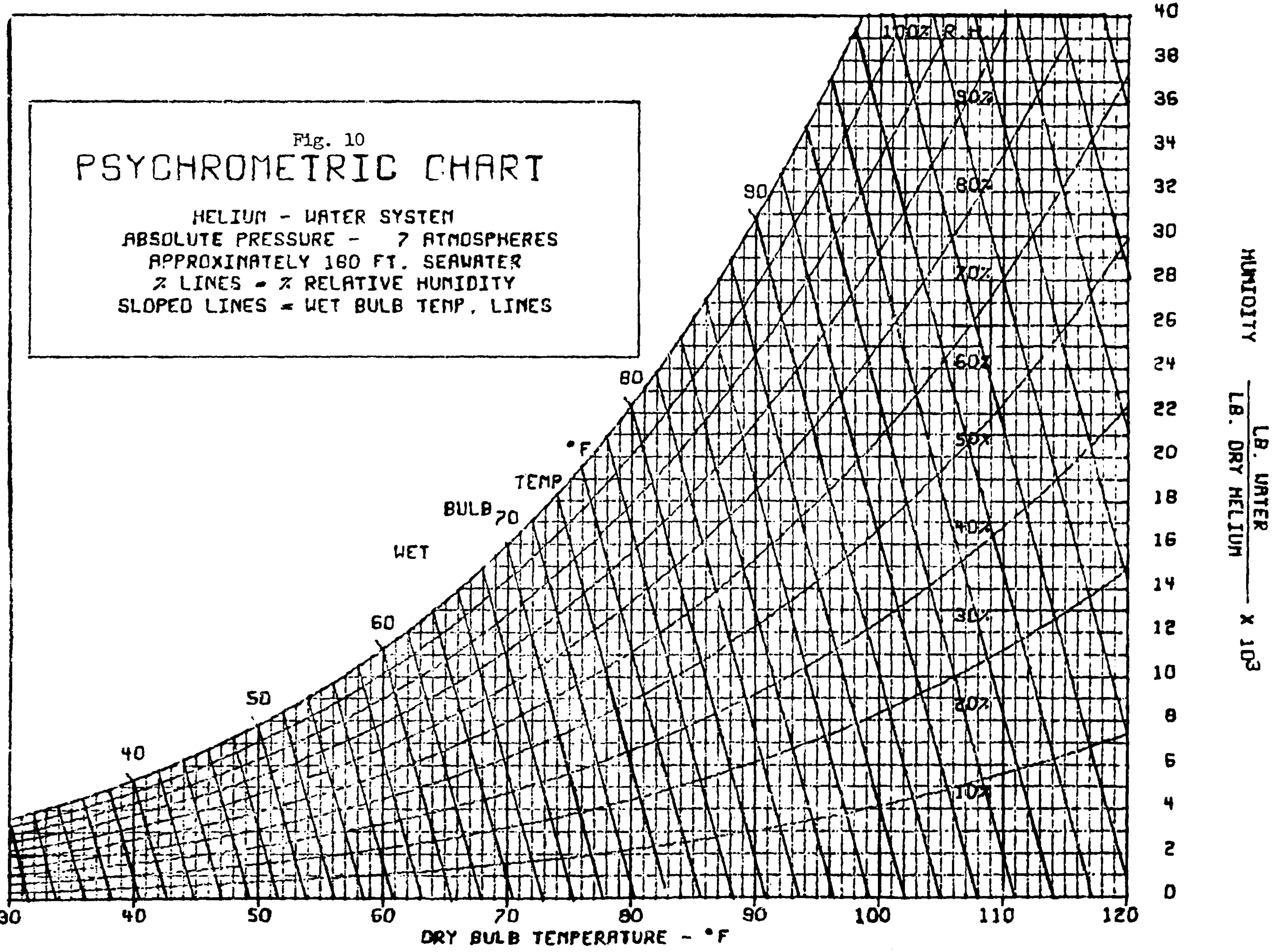


Fig. 10

PSYCHROMETRIC CHART

HELIUM - WATER SYSTEM
ABSOLUTE PRESSURE - 7 ATMOSPHERES
APPROXIMATELY 160 FT. SEAWATER
% LINES = % RELATIVE HUMIDITY
SLOPED LINES = WET BULB TEMP. LINES

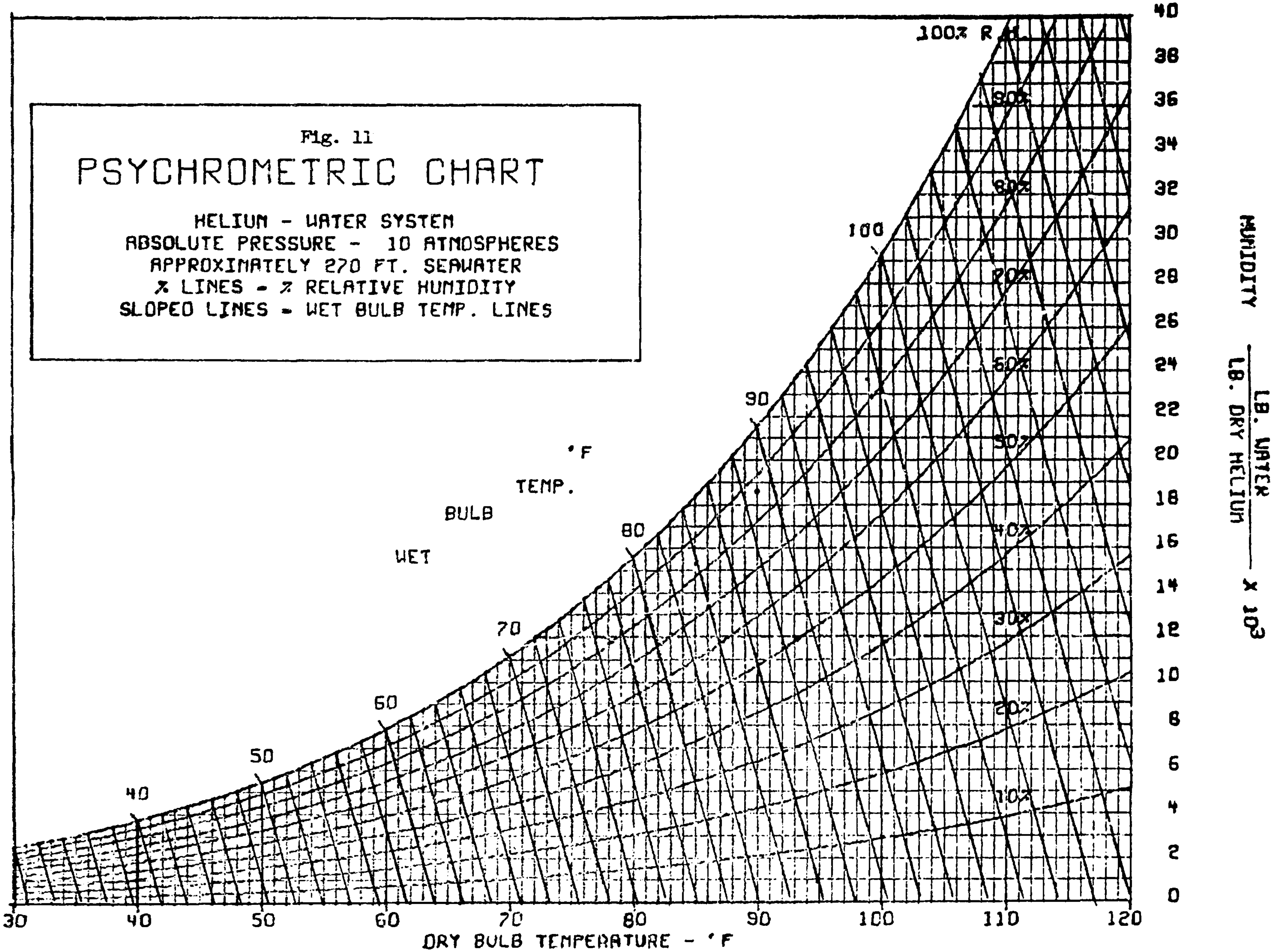


Fig. 11

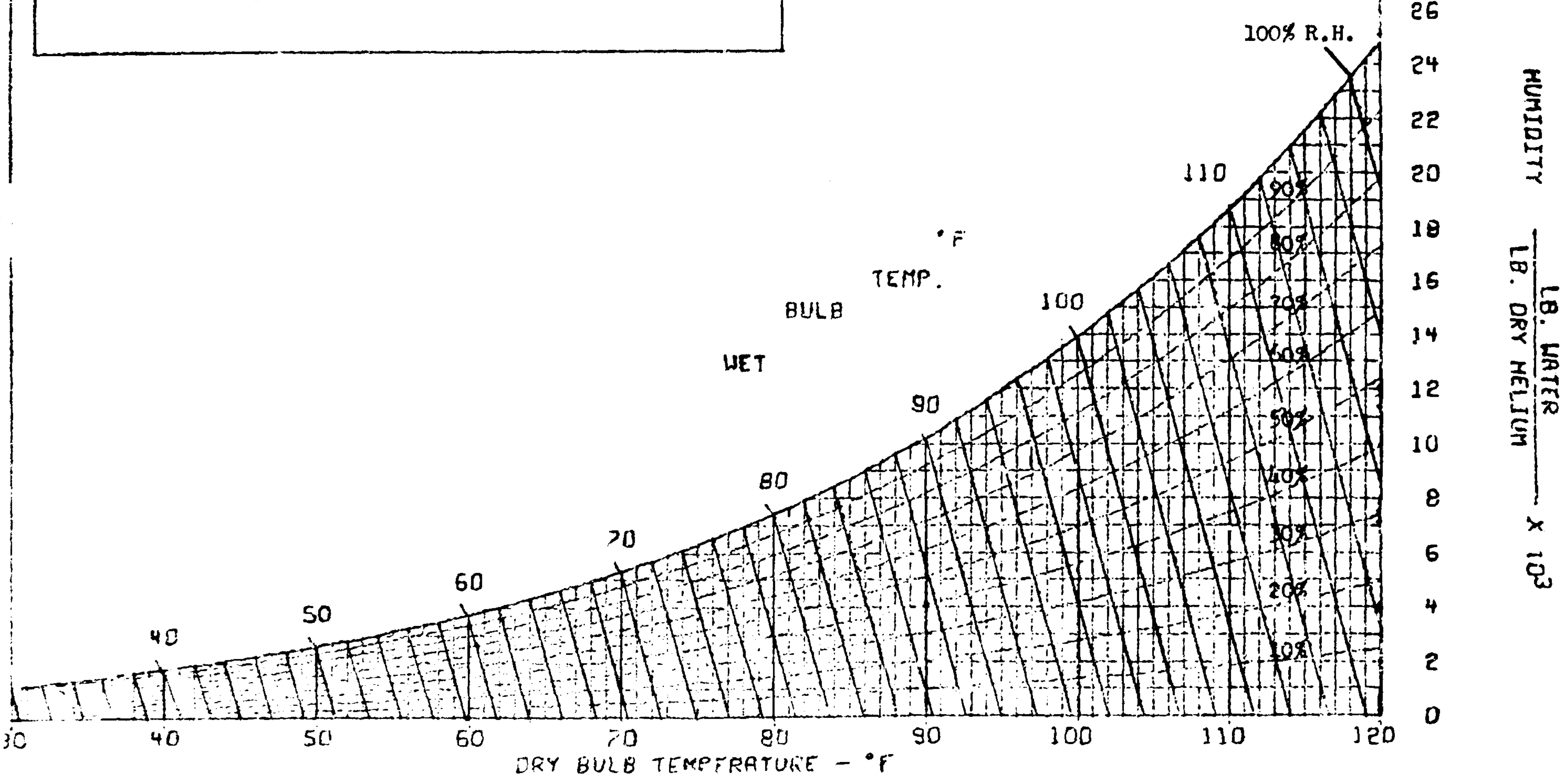
PSYCHROMETRIC CHART

HELIUM - WATER SYSTEM
ABSOLUTE PRESSURE - 10 ATMOSPHERES
APPROXIMATELY 270 FT. SEAWATER
% LINES - % RELATIVE HUMIDITY
SLOPED LINES - WET BULB TEMP. LINES

Fig. 12

PSYCHROMETRIC CHART

HELIUM - WATER SYSTEM
ABSOLUTE PRESSURE - 21 ATMOSPHERES
APPROXIMATELY 600 FT. SEAWATER
% LINES = % RELATIVE HUMIDITY
SLOPED LINES - WET BULB TEMP. LINES



NOMENCLATURE

A = area, sq.ft.

atm. = atmosphere

D = diameter

DG/μ = Reynolds number

EH = Electric Hygrometer

$^{\circ}$F. = degrees Fahrenheit

G = lb. dry air/hr.

h = heat-transfer coefficient, B.t.u./(hr. x sq.ft. x $^{\circ}$F.)

H_1 = initial humidity of the air, lb. water vapor/lb. dry air

H_2 = final humidity of the air, lb. water vapor/lb. dry air

H_g = humidity of the gas stream, lb. vapor/lb. vapor-free gas

H_s = humidity of saturated air at adiabatic saturation temperature

H_w = humidity of gas saturated at the wet-bulb temperature, lb. vapor/lb. vapor-free gas

hr. = hour

k = mass-transfer coefficient, lb.-moles/(hr. x sq.ft. x unit mole fraction difference)

K = psychrometric constant

$\bar{K}$ = average value of the psychrometric constant K

K' = psychrometric constant in simplified equation

min. = minute

MM = Moisture Monitor

N = number of points

N_w/θ = rate of water evaporation, lb.-moles/hr.

P = total pressure

p_a = partial pressure of water vapor in gas measured at t_a and P_a

P_a = atmospheric pressure

P_b = bourdon gauge pressure

p_g = partial pressure of water vapor in the gas stream

p_s = partial pressure of vapor in saturated vapor-gas mixture at the dry-bulb temperature. (This is equal to the vapor pressure of the liquid at t_g.)

$p_{sat.}$ = vapor pressure of water at t_a

p_w = partial pressure of water vapor in gas saturated at the wet-bulb temperature. (This is equal to the vapor pressure of water at the wet-bulb temperature.)

ppm. = parts per million by volume

Q/θ = heat transferred, B.t.u./hr.

RH = relative humidity, %

$s(K)$ = standard deviation of K

sq.ft. = square feet

t_a = temperature at which humidity is measured, °F.

t_g = dry-bulb temperature (temperature of the gas), °F.

t_{g1} = initial temperature of the air, °F.

t_{g2} = final temperature of the air, °F.

t_s = adiabatic saturation temperature, °F.

t_w = wet-bulb temperature, °F.

X_g = mole fraction of water vapor in the gas stream

X_w = mole fraction of water vapor in saturated gas at the wet-bulb temperature

λ_s = latent heat of vaporization of water at the adiabatic saturation temperature, B.t.u./lb.

λ_w = latent heat of vaporization of water at the wet-bulb temperature B.t.u./lb.

μ = viscosity

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APPENDIX

```
//CONIXX JOB    T234,'ROBERT C RAMSEY
//STEP1  EXEC  PLOTECLG
//FORT.SYSIN   DD *
C     PROGRAM TO PLOT PSYCHROMETRIC CHARTS FOR VARIOUS LIQUID-GAS SYSTEMS
C     DRY BULB TEMP RANGE RESTRICTED TO 30 TO 120 DEG. F
C     YMIN = MINIMUM HUMIDITY PLOTTED (USUALLY 0.000)
C     YMAX = MAXIMUM HUMIDITY VALUE TO BE PLOTTED
C     (YMAX-YMIN)*1000 MUST BE DIVISIBLE BY 40
C     YL  = REQUIRED PHYSICAL LENGTH OF Y AXIS INCHES
C     YD   = Y INCREMENT  (HERE = TO YMAX)
C     P    =  TOTAL PRESSURE  INCHES HG
C     CON = APPROPRIATE PSYCHROMETRIC CONSTANT
      DIMENSION PRES(120)
      COMMON PRES,PS
      READ (1,1) (PRES(L),L=1,120)
    1 FORMAT (10F8.5)
   36 READ(1,35)YMIN,YMAX,YL,YD,P,CON
   35 FORMAT (8F10.0)
      IC = 201
      ICC=90
      UNIT=(YMAX-YMIN)/40.
      IF(P-0.0)  2,37,2
    2 CALL PLOT(IC,30.,120.,9.,90.,YMIN,YMAX,YL,YD )
C     LABEL T SCALE
      Y=YMIN-1.*UNIT
      CALL PLOT(ICC,29.0,Y)
      WRITE(4,3)
      CALL CHAR(0.1.0)
    3 FORMAT('30        40        50        60        70
     1  90        100       110       120',100X)
      X=30.
      Y=YMIN-0.3*UNIT
      DO 70 L=1,10
      CALL PLOT (ICC,X,YMIN)
      CALL PLOT (ICC,X,Y)
      CALL PLOT (99)
      X=X+10.
   70 CONTINUE
C     LABEL HU SCALE
      HU=YMIN
      IHU=YMIN
      DL=YMAX/40.
      IDL=DL*1000.01
      DO 4 J=1,21
      CALL PLOT(ICC,121.,HU)
      WRITE(4,5) IHU
      CALL CHAR(0.1.0)
    5 FORMAT(I3,100X)
      CALL PLOT(99)
      IHU=IHU+2*IDL
    4 HU=HU+2.*UNIT
C     LABEL HU AXIS
      Y=YMIN+14.*UNIT
      CALL PLOT(ICC,128 ,Y)
```

```
      WRITE (4;6)
      CALL CHAR(0.1,1)
    6 FORMAT('HUMIDITY',100X)
      Y=YMIN+20.*UNIT
      CALL PLOT(ICC,127.5,Y)
      Y=YMIN+30.*UNIT
      CALL PLOT(ICC,127.5,Y)
      CALL PLOT(99)
      Y=YMIN+22.*UNIT
      CALL PLOT(ICC,127.,Y)
      WRITE (4,7)
      CALL CHAR(0.1,1)
    7 FORMAT('LB. WATER',100X)
      Y=YMIN+20.5*UNIT
      CALL PLOT(ICC,129.,Y)
      WRITE(4,8)
      CALL CHAR(0.1,1)
    8 FORMAT ('LB. DRY HELIUM',100X)
      Y=YMIN+30.5*UNIT
      CALL PLOT(ICC,128.,Y)
      WRITE( 4,60)
      CALL CHAR(0.1,1)
   60 FORMAT('X 10',100X)
      Y=YMIN+32.6*UNIT
      CALL PLOT(ICC,127.5,Y)
      WRITE(4,61)
      CALL CHAR(0.1,1)
   61 FORMAT('3',100X)
C     LABEL T AXIS
      Y=YMIN-2.*UNIT
      CALL PLOT(ICC,63.,Y)
      WRITE (4,9)
      CALL CHAR(0.1,0)
    9 FORMAT ('DRY BULB TEMPERATURE - ZF',100X)
      CALL PLOT(99)
C     PLOT RH LINES
      DO 12 L=1,10
      CENT=L/10.
      DO 10 K=30,120
      HU=4.5006*CENT*PRES(K)/(P-CENT*PRES(K))
      IF(HU-YMAX)   42,42,11
   42 TK=K
      CALL PLOT(ICC,TK,HU)
   10 CONTINUE
   11 CALL PLOT(99)
   12 CONTINUE
C     LABEL RH LINES
      MRH=10
      Y=YMIN+4.5*UNIT
      DO 71 M=1,9
      AT=P/29.921
      XA=98. +AT
      CALL PLOT(ICC.XA ,Y)
      WRITE(4,72)  MRH
```

```
      CALL CHAR(0.1,0)
   72 FORMAT(I3,''',100X)
      MRH=MRH+10
      IF(M-5)  74,73,74
   73 Y=Y+3.5*UNIT
      GO TO 71
   74 Y=Y+4.*UNIT
   71 CONTINUE
      Y=YMIN+39.*UNIT
      X=XA-5.
      CALL PLOT(ICC,X   ,Y)
      WRITE(4,75)
      CALL CHAR(0.1,0)
   75 FORMAT('100' R.H.',100X)
      CALL PLOT(99)
C     PLOT VERTICAL GRID
      DO 13 M=30,120
      TM=M
      HU=4.5006*PRES(M)/(P-PRES(M))
      IF(HU-YMAX)   41,40,40
   40 HU=YMAX
   41 CALL PLOT (ICC,TM,0.000)
      CALL PLOT(ICC,TM,HU)
      CALL PLOT(99)
   13 CONTINUE
      CALL PLOT(ICC,30.,YMIN)
      CALL PLOT(ICC,30.,YMAX)
      CALL PLOT(99)
C      PLOT HORIZONTAL GRID
      HU=0.000
      DO 14 N=1,40
      PS=HU*P/(HU+4.5006)
      IF(PS-PRES(60))  43,15,15
   43 IF(PS-PRES(30))  44,16,16
   44 DO 17 M3=1,29
      IF(PS-PRES(M3))  17,45,45
   45 IF(PS-PRES(M3+1)) 18,17,17
   17 CONTINUE
   18 CALL FIG(M3,TW)
      GO TO 30
   16 DO 19 M2=30,59
      IF(PS-PRES(M2))  19,46,46
   46 IF(PS-PRES(M2+1))  20,19,19
   19 CONTINUE
   20 CALL FIG(M2,TW)
      GO TO 30
   15 IF(PS-PRES(90))  47,21,21
   47 DO 22 M4=60,89
      IF(PS-PRES(M4))  22,48,48
   48 IF(PS-PRES(M4+1))  23,22,22
   22 CONTINUE
   23 CALL FIG(M4,TW)
      GO TO 30
   21 DO 24 M1=90,119
```

```
      IF(PS-PRES(MI))  24,49,49
   49 IF(PS-PRES(MI+1))  25,24,24
   24 CONTINUE
   25 CALL FIG (MI,TW)
      GO TO 30
   30 IF(TW-30.0)  50,55,55
   50 TW=30.0
   55 CALL PLOT (ICC,120.,HU)
      CALL PLOT (ICC,TW,HU)
      CALL PLOT(99)
      HU = HU+UNIT
   14 CONTINUE
      CALL PLOT (ICC,120.,YMAX)
      CALL PLOT (ICC,30.,YMAX)
      CALL PLOT(99)
C     PLOT WB LINES
      WRITE (3,38)
   38 FORMAT (20X,'PLOTTING WET BULB LINES  *     *     *     *',2X)
      KOUNT = -2
      DO 26 NTW=30,120,2
      KOUNT=KOUNT+2
   28 TW=NTW
      HU=4.5006*PRES(NTW)/(P-PRES(NTW))
      IF(HU-YMAX )  53,53,52
   52 HU=YMAX
   53 HUU=HU
      CALL PLOT (ICC,TW,HU)
      DO 29 JJ=1,41
      IF(HU-0.00)  31,62,62
   62 PSD=HU*P/(HU+4.5006)
      TDB=TW+(1093.8-0.576*TW)*(PRES(NTW)-PSD)/(CON  *P)
      IF(TDB-120.) 54,31,31
   54 CALL PLOT (ICC,TDB,HU)
      HU=HU-UNIT
   29 CONTINUE
   31 CALL PLOT(99)
      II=NTW
      IF(II-99)  76,76,26
   76 IF(KOUNT-10)  26,27,26
   26 CONTINUE
C     WRITE WET BULB TEMP ZF
      Y=YMIN+15.3*UNIT
      CALL PLOT(ICC,60.7,Y)
      WRITE (4,77)
      CALL CHAR(0.1,0)
   77 FORMAT('WET',100X)
      Y=YMIN+17.3*UNIT
      CALL PLOT(ICC,64.7,Y)
      WRITE(4,78)
      CALL CHAR(0 1,0)
   78 FORMAT('BULB',100X)
      Y=YMIN+18.5*UNIT
      CALL PLOT(ICC,70.4,Y)
      WRITE(4,79)
```

```
      CALL CHAR(0.1,0)
   79 FORMAT('TEMP.',100X)
      Y=YMIN+20.*UNIT
      CALL PLOT(ICC,74.7,Y)
      WRITE (4,80)
      CALL CHAR(0.1,0)
   80 FORMAT('ZF',100X)
      CALL PLOT (99)
C     WRITE NAME PLATE
      Y=YMIN+24.5*UNIT
      CALL PLOT(ICC,31.5,Y)
      CALL PLOT(ICC,80.5,Y)
      Y=YMIN+36.*UNIT
      CALL PLOT(ICC,80.5,Y)
      CALL PLOT(ICC,31.5,Y)
      Y=YMIN+24.5*UNIT
      CALL PLOT(ICC,31.5,Y)
      CALL PLOT(99)
      Y=YMIN+26.5*UNIT
      CALL PLOT(ICC,38.5,Y)
      WRITE(4,81)
      CALL CHAR(0.1,0)
   81 FORMAT('SLOPED LINES = WET BULB TEMP. LINES',100X)
      Y=YMIN+27.5*UNIT
      CALL PLOT(ICC,41.5,Y)
      WRITE(4,82)
      CALL CHAR(0.1,0)
   82 FORMAT('' LINES = ' RELATIVE HUMIDITY',100X)
      IAT=P/29.9205
      IFT=(IAT-1)*30
      Y=YMIN+28.5*UNIT
      CALL PLOT(ICC,41.,Y)
      WRITE(4,83) IFT
      CALL CHAR(0.1,0)
   83 FORMAT('APPROXIMATELY ',I3,' FT. SEAWATER',100X)
      Y=YMIN+29.5*UNIT
      CALL PLOT(ICC,39.,Y)
      WRITE (4,84) IAT
      CALL CHAR(0.1,0)
   84 FORMAT('ABSOLUTE PRESSURE - ',I3,' ATMOSPHERES',100X)
      Y=YMIN+30.5*UNIT
      CALL PLOT(ICC,44.5,Y)
      WRITE (4,85)
      CALL CHAR(0.1,0)
   85 FORMAT('HELIUM - WATER SYSTEM',100X)
      Y=YMIN+32.5*UNIT
      CALL PLOT(ICC,35.,Y)
      WRITE(4,86)
      CALL CHAR(0.2,0)
   86 FORMAT('PSYCHROMETRIC CHART',100X)
      Y=YMIN-2.6*UNIT
      CALL PLOT(ICC,23.6,Y)
      CALL PLOT(ICC,133.4,Y)
      YY = YMIN+42.6*UNIT
```

```
      CALL PLOT(ICC,133.4,YY)
      CALL PLOT(ICC,23.6,YY)
      CALL PLOT(ICC,23.6,Y)
      CALL PLOT(99)
      GO TO 34
C     LABEL WET BULB LINES
   27 X=TW-2.
      Y=HUU+1.*UNIT
      CALL PLOT(ICC,X,Y)
      WRITE(4,33)  II
      CALL CHAR (0.1.0)
   33 FORMAT(I3,100X)
      CALL PLOT(99)
      XX=TW-0.5
      YY=HUU+0.4*UNIT
      CALL PLOT(ICC,TW,HUU)
      CALL PLOT(ICC,XX,YY)
      CALL PLOT(99)
      KOUNT=0
      GO TO 26
   34 CALL PLOT(7)
      GO TO 36
   37 CALL PLOT(100)
      STOP
      END
      SUBROUTINE FIG(MM,TW)
      DIMENSION PRES(120)
      COMMON PRES,PS
      TW=MM
      DEL=(PS-PRES(MM))/(PRES(MM+1)-PRES(MM))
      TW=TW+DEL
      RETURN
      END
```

DATA

```
/*
//GO.SYSIN    DD *
  .04693  .04917  .05150  .05393  .05646  .05911  .06186  .06472  .06771  .07081
  .07404  .0774[illegible]  .08090  .08454  .08833  .09226  .09636  .10060  .10502  .10961
  .11438  .11932  .12447  .12980  .13534  .14109  .14705  .15324  .15966  .16631
  .17321  .18035  .18776  .19546  .20342  .21166  .22019  .22905  .23819  .24766
  .25747  .26761  .27812  .28899  .30021  .31183  .32385  .33627  .34909  .36237
  .37607  .39024  .40486  .41997  .43558  .45169  .46832  .48548  .50321  .52150
  .54038  .55984  .57991  .60062  .62198  .64399  .66667  .69006  .71417  .73901
  .76460  .79095  .81811  .84608  .87485  .90449  .93499  .96643  .99876 1.03200
 1.06630 1.10150 1.13770 1.17490 1.21320 1.25260 1.29310 1.33470 1.37750 1.42150
 1.46570 1.51310 1.56080 1.60980 1.66010 1.71180 1.76480 1.81930 1.87530 1.93270
 1.99160 2.05210 2.11420 2.17880 2.24320 2.31030 2.37900 2.44950 2.52180 2.59590
 2.67190 2.74970 2.82950 2.91140 2.99520 3.08110 3.16910 3.25930 3.35170 3.44630
     0.000     0.320       7.5     0.320   29.9210      .470
     0.000     0.080       7.5     0.080   119.684      .470
     0.000     0.040       7.5     0.040   209.447      .470
     0.000     0.040       7.5     0.040   299.210      .470
     0.000     0.040       7.5     0.040   628.341      .470
     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
/*
```

```
//CONIXX JOB    T234,'ROBERT C RAMSEY
//STEP1  EXEC  FORTGCDK
//FORT.SYSIN   DD *
C                         PROGRAM TO REDUCE RAW DATA
C
C
C     JDAT = DAY OF MONTH
C     CODE = 1 = AIR             CODE = 2 = HELIUM
C     ATM = ATMOSPHERIC PRESSURE IN INCHES OF MERCURY
C     GAGE = GAGE PRESSURE IN POUNDS PER SQUARE INCH
C     WB = WET BULB TEMPERATURE IN MILLIVOLTS, COPPER-CONSTINTAN
C     DB = DRY BULB TEMPERATURE IN MILLIVOLTS, COPPER-CONSTINTAN
C     TRH = TEMPERATURE AT WHICH RELATIVE HUMIDITY WAS TAKEN IN DEG. F
C     RH = RELATIVE HUMIDITY DIVIDED BY 100
C     PPM = PARTS PER MILLION WATER VAPOR BY VOLUME  BY DEW PT. HYGRMETR
C     DELH = DIFFERENCE IN HEAD ON WATER FEED IN INCHES OF WATER
C     DROPS = FEED RATE OF WATER IN DROPS PER MINUTE
C     VEL = FLOW RATE IN CUBIC FEET PER MINUTE
      DIMENSION TEM(120),PRES(120)
      COMMON TEM,PRES,WB
      INTEGER  TRIP,CODE
      M=0
  999 OD=2.5
      DIA=.430
      WRITE(3,9)
    9 FORMAT (1H1)
      READ(1,50) JDAT,CODE,PPCOR,RHCOR
   50 FORMAT(I2,I1,2F8.0)
      IF(CODE.EQ.1)   GO TO 80
      WRITE (3,55)  JDAT
   55 FORMAT (2X,'PURPOSE=CHECK OUT NEW APPARATUS WITH HELIUM      ******
     1                 ',20X,'DATE 5/',I2,'/68  ',//)
      GO TO 81
   80 WRITE (3,82) JDAT
   82 FORMAT (2X,'PURPOSE=CHECK OUT NEW APPARATUS WITH AIR         ******
     1                 ',20X,'DATE 5/',I2,'/68  ',//)
   81 WRITE (3,11)
   11 FORMAT(2X,'PRESS   HG',4X,'REL HUM AT P',4X,'AT TEM OF ',4X,'MASS
     1 VEL',4X,'DEL H H2O ',4X,'DROPS MIN ',4X,'DB DEG F   ',4X,'WB DEG F
     2  ',4X,'CONST  K  ',///)
   15 READ (1,17)  (TEM(J),J=1,120)
   17 FORMAT (10F8.4)
      READ  (1,18) (PRES(L),L=1,120)
   18 FORMAT  (10F8.5)
    8 READ (1,19)  ATM,GAGE,WB,DB,TRH,RH,PPM,DELH,DROPS,VEL
   19 FORMAT (10F8.0)
      ERH=RH
      PPM =(PPM-PPCOR)*.000001
      RH=RH-RHCOR
      GAGE = GAGE*29.921/14.696
      P=ATM+GAGE
      IF(DB.EQ.0.00)   GO TO 10
      TRIP = 1
   99 IF (WB.GE.TEM(50))   GO TO 1
```

```
      IF (WB.GE.TEM(25))   GO TO 3
      DO 4   M3 = 1.24
      IF (WB.GE.TEM(M3).AND.WB.LT.TEM(M3+1))   GO TO 21
    4 CONTINUE
   21 CALL  FIG (M3.WB1.$30)
    3 DO 5  M2=25.49
      IF (WB.GE.TEM(M2).AND.WB.LT.TEM(M2+1))   GO TO 22
    5 CONTINUE
   22 CALL  FIG (M2.WB1.$30)
    1 IF (WB.GE.TEM(75))   GO TO 2
      DO 6 M4=50.74
      IF (WB.GE.TEM(M4).AND.WB.LT.TEM(M4+1 )   GO TO 23
    6 CONTINUE
   23 CALL FIG (M4.WB1.$30)
    2 DO 7 M1=75.119
      IF (WB.GE.TEM(M1).AND.WB.LT.TEM(M1+1))   GO TO 24
    7 CONTINUE
   24 CALL FIG (M1.WB1.$30)
   30 IF (TRIP.EQ.2)  GO TO 97
      WET = WB1
      IP = WET
      PEL = (WET-IP)*(PRES(IP+1)-PRES(IP))
      PS = PRES(IP)+PEL
      ITR = TRH
      TEL=(TRH-ITR)*(PRES(ITR+1)-PRES(ITR))
      PSS=PRES(ITR)+TEL
      DO 98 KKK=1.2
      IF(KKK.EQ.1)   PIS=RH*PSS*P/ATM
      IF(KKK.EQ.2)   PIS = PPM*P
   44 IF (TRIP.EQ.1)  GO TO 98
      IF(TRIP.EQ.2)  GO TO 97
   98 TRIP = 2
      WB = DB
      GO TO 99
   97 TDB=WB1
      IDB = TDB
      BEL=(TDB-IDB)*(PRES(IDB+1)-PRES(IDB))
      PSD=PRES(IDB)+BEL
   89 DMW = TDB-WET
      CON = (PS-PIS)*(1093.8-0.576*WET)/(P*(DMW))
      DD=DIA**2-(OD/25.4)**2
      MSV = VEL*110./DD
      IF (CODE.EQ.2)  GO TO 83
      MSV = VEL*801./DD
   83 RH=(PIS/PSD)*100.
      IF(KKK.EQ.1)  WRITE(3,111) PIS,PS,DMW
      IF(KKK.EQ.2)   WRITE (3,222)  PIS,PS,DMW
  111 FORMAT (2X,'RH METER USED       PIS=',F10.5,'    P SATD =',F10.5,'
     1 DB - WB =',F10.2,/)
  222 FORMAT (2X,'DEW POINT HYGROMETER USED      PIS=',F10.5,'    P SATD =
     1',F10.5,'    DB - WB =',F10.2,/)
      IF(KKK.EQ.1)
     1CONU=((PS+0.00119)-(ERH-0.015)*(PSS-0.00172)*(P-0.4)/(ATM+0.04))*(
     2(1093.8+0.05)-(0.576-0.0005)*(WET-0.02))/((P-0.4)*((TDB-0.02)-(WET
```

```
     3-0.02)))
      IF(KKK.EQ.1)
     1CONM=((PS-0.00119)-(ERH+0.015)*(PSS+0.00172)*(P+0.4)/(ATM-0.04))*(
     2(1093.8-0.05)-(0.576+0.0005)*(WET+0.02))/((P+0.4)*((TDB+0.02)-(WET
     3-0.02)))
      IF(KKK.EQ.2)     M=M+1
      IF(KKK.EQ.2.AND.M.LE.4)
     1CONU=((PS+0.00119)-(PPP-.000500)*(P-0.4)                           )*(
     2(1093.8+0.05)-(0.576-0.0005)*(WET-0.02))/((P-0.4)*((TDB-0.02)-(WET
     3+0.02)))
      IF(KKK.EQ.2.AND.M.LE.4)
     1CONM=((PS-0.00119)-(PPM+0.000500)*(P+0.4)                           )*(
     2(1093.8-0.05)-(0.576+0.0005)*(WET+0.02))/((P+0.4)*((TDB+0.02)-(WET
     3-0.02)))
      IF(KKK.EQ.2.AND.M.GE.5)
     1CONU=((PS+0.00119)-(PPP-.000150)*(P-0.4)                           )*(
     2(1093.8+0.05)-(0.576-0.0005)*(WET-0.02))/((P-0.4)*((TDB-0.02)-(WET
     3+0.02)))
      IF(KKK.EQ.2.AND.M.GE.5)
     1CONM=((PS-0.00119)-(PPM+0.000150)*(P+0.4)                           )*(
     2(1093.8-0.05)-(0.576+0.0005)*(WET+0.02))/((P+0.4)*((TDB+0.02)-(WET
     3-0.02)))
      PERU=(CONU/CON - 1 )*100.
      PERM=(1.-CONM/CON)*100.
      WRITE(3,500)CONU,PERU,CONM,PERM
  500 FORMAT(2X,'K, MAX PLUS ERROR =',F10.4,'  PERCENT ERROR =',F10.2,5X
     1,'K, MAX MINUS ERROR =',F10.4,'  PERCENT ERROR =',F10.2,/)
      SS=CON**2
      WRITE (3,501)  SS
  501 FORMAT (5X,'CON SQUARED =',F10.8,/)
      WRITE (3,12) P,RH,TDB,MSV,DELH,DPOPS,TDB,WET,CON
   88 CONTINUE
   12 FORMAT (2X,F10.2,4X,F10.1,4X,F10.2,4X,I10,4(4X,F10.2),4X,F10.4,//)
      GO TO 8
   10 CALL EXIT
      END
      SUBROUTINE  FIG(MM,WB1,*)
      DIMENSION TEM(120),PRES(120)
      COMMON TEM,PRES,WB
      WB1=MM
      DEL=(WB-TEM(MM))/(TEM(MM+1)-TEM(MM))
      WB1=WB1+DEL
      RETURN 1
      END
```

DATA

```
/*
//GO.SYSIN      DD *
132    000.     .000
  -.6490   -.6290   -.6080   -.5880   -.5670   -.5460   -.5260   -.5050   -.4840   -.4630
  -.4420   -.4210   -.4010   -.3800   -.3590   -.3390   -.3180   -.2970   -.2750   -.2540
  -.2330   -.2120   -.1910   -.1700   -.1490   -.1280   -.1070   -.0850   -.0640   -.0420
  -.0210    .0000    .0210    .0420    .0640    .0860    .1070    .1290    .1500    .1710
   .1930    .2150    .2360    .2580    .2800    .3020    .3240    .3460    .3670    .3890
   .4110    .4330    .4550    .4770    .4990    .5210    .5430    .5650    .5870    .6090
   .6310    .6540    .6760    .6980    .7200    .7430    .7650    .7870    .8090    .8320
   .8540    .8770    .8990    .9220    .9440    .9670    .9900   1.0120   1.0350   1.0570
  1.0800   1.1030   1.1260   1.1480   1.1710   1.1940   1.2170   1.2400   1.2630   1.2860
  1.3090   1.3320   1.3550   1.3780   1.4010   1.4240   1.4480   1.4710   1.4940   1.5170
  1.5400   1.5630   1.5870   1.6100   1.6330   1.6570   1.6800   1.7040   1.7270   1.7510
  1.7740   1.7980   1.8210   1.8450   1.8690   1.8930   1.9160   1.9400   1.9630   1.9870
  .04693   .04917   .05150   .05393   .05646   .05911   .06186   .06472   .06771   .07081
  .07404   .07741   .08090   .08454   .08833   .09226   .09636   .10060   .10502   .10961
  .11438   .11932   .12447   .12980   .13534   .14109   .14705   .15324   .15965   .16631
  .17321   .18035   .18776   .19546   .20342   .21166   .22019   .22905   .23819   .24766
  .25747   .26761   .27812   .28899   .30021   .31183   .32385   .33627   .34907   .36237
  .37607   .39024   .40486   .41997   .43558   .45169   .46832   .48548   .50321   .52150
  .54038   .55984   .57991   .60062   .62199   .64399   .66667   .69006   .71417   .73901
  .76460   .79095   .81811   .84608   .87485   .90449   .93499   .96643   .99876  1.03200
 1.06630  1.10150  1.13770  1.17490  1.21320  1.25260  1.29310  1.33470  1.37750  1.42150
 1.46670  1.51310  1.56030  1.60980  1.66010  1.71180  1.76480  1.81930  1.87530  1.93270
 1.99160  2.05210  2.11420  2.17580  2.24320  2.31030  2.37900  2.44950  2.52180  2.59590
 2.67190  2.74970  2.82950  2.91140  2.99520  3.08110  3.16910  3.25930  3.35170  3.44630
   30.16    25.20   0.8737   1.1075     87.0    .1190    5010.    -6.00      0.0     6.00
   30.16    25.40   0.8773   1.1123     87.0    .1185    5100.    -6.00      0.0     6.20
   30.16    25.40   0.8777   1.1182     87.0    .1160    5100.    -6.00      0.0     6.20
   30.16    24.00   0.8767   1.1219     87.0    .1190    5200.    -6.00      0.0     5.80
   30.41    43.70   0.8624   1.0393     82.5    .0710    2450.    -5.50      0.0     6.40
   30.41    44.00   0.8595   1.0386     82.5    .0710    2670.    -5.50      0.0     6.10
   30.41    44.80   0.8572   1.0433     83.0    .0710    2940.    -5.50      0.0     6.30
   30.41    44.80   0.8715   1.0487     83.0    .0710    3100.    -5.50      0.0     6.15
```

```
 30.14   25.80  0.7268  1.1223    87.0   .0000    740.  -6.00     0.0    6.00
 30.14   25.50  0.7284  1.1302    87.0   .0000    640.  -6.00     0.0    6.30
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13. ABSTRACT

When gas that is not saturated with water is passed over a wetted surface, the surface temperature will drop because of evaporation of water. This drop in temperature (often called the wet-bulb depression) together with the temperature of the gas stream gives a measure of the humidity of the gas. For many years, psychrometers based on this phenomenon have been used very successfully for measuring the humidity of air under the usual conditions of temperature and pressure encountered by most people on earth.

In recent years, with man's increasing interest in exploring the ocean at greater and greater depths, it was found necessary to replace the nitrogen of the normal atmosphere with helium to provide a breathing gas for those living at ambient ocean pressure. This led to a need for a knowledge of the psychrometric properties of helium at pressures up to several hundred pounds per square inch.

This investigation has resulted in: (1) the development of an improved psychrometer, (2) the development of a psychrometric equation for the helium-water vapor system, and (3) the development of a computer program which makes it possible to print out psychrometric charts for any ocean depth.

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